FUNDAMENTALS OF
AEROSPACE MEDICINE

FOURTH EDITION

Jeffrey R. Davis
Robert Johnson
Jan Stepanek
Jennifer A. Fogarty

Wolters Kluwer Health | Lippincott Williams & Wilkins

FOURTH EDITION

FUNDAMENTALS OF AEROSPACE MEDICINE

EDITORS

Jeffrey R. Davis, MD, MS
Professor
Preventive Medicine and Community Health
The University of Texas Medical Branch
Galveston, Texas

Jan Stepanek, MD, MPH
Assistant Professor
Medical Director Aerospace Medicine Program
Division of Preventive, Occupational and Aerospace Medicine
Department of Internal Medicine
Mayo Clinic
Scottsdale, Arizona;
Assistant Professor
Preventive Medicine and Community Health
The University of Texas Medical Branch
Galveston, Texas

Robert Johnson, MD, MPH, MBA
Associate Professor
Preventive Medicine and Community Health
The University of Texas Medical Branch;
Staff Physician
Aviation Medical Center
University of Texas Medical Branch University Hospitals
Galveston, Texas

Jennifer A. Fogarty, PhD
Adjunct Assistant Professor
Preventive Medicine and Community Health
The University of Texas Medical Branch
Galveston, Texas;
Biomedical Risk Coordinator
Space Medicine Division
NASA
Houston, Texas

Wolters Kluwer Health | Lippincott Williams & Wilkins

Philadelphia • Baltimore • New York • London
Buenos Aires • Hong Kong • Sydney • Tokyo

Acquisitions Editor: Sonya Seigafuse
Managing Editor: Kerry Barett
Project Manager: Nicole Walz
Manufacturing Manager: Kathy Brown
Marketing Manager: Kim Schonberger
Design Coordinator: Terry Mallon
Cover Designer: Joseph DePinho
Production Services: Laserwords Private Limited, Chennai, India

530 Walnut Street
Philadelphia, PA 19106 USA
LWW.com

Credit Lines for Cover Photos

From Top to Bottom:

SpaceShipTwo: Courtesy of Virgin Galactic
International Space Station: Courtesy of NASA Marshall Space Flight Center (NASA-MSFC)
Apollo Soyuz: Courtesy of NASA Marshall Space Flight Center (NASA-MSFC)
Mercury Capsule: Courtesy of NASA Headquarters—Greatest Images of NASA (NASA-HQ-GRIN)
SR-71: Courtesy of NASA Dryden Flight Research Center (NASA-DFRC)
Bell X-1: Courtesy of NASA Headquarters—Greatest Images of NASA (NASA-HQ-GRIN)
Ford Tri-motor: Courtesy of NASA Langley Research Center (NASA-LaRC)
Wright Flyer: Courtesy of NASA Marshall Space Flight Center (NASA-MSFC)

Printed in the USA

Library of Congress Cataloging-in-Publication Data

Fundamentals of aerospace medicine / editors, Jeffrey R. Davis . . . [et al.].—4th ed.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-0-7817-7466-6
1. Aviation medicine. 2. Space medicine. I. Davis, Jeffrey R.
[DNLM: 1. Aerospace Medicine. 2. Space Flight. WD 700 F981 2008]
RC1062.F86 2008
616.9′8021—dc22

2008003374

---

10 9 8 7 6 5 4 3 2 1

FOREWORD

Unlike most Forewords, I have elected to commence by going backward. For the benefit of the reader of this fourth edition of "Fundamentals" I begin with a very brief review of this texts' progenitors.

The foundation for this series of textbooks was laid by Dr. Louis Bauer in 1926 when he published the first volume on this topic in the United States—*Aviation Medicine*. Dr. Bauer also played an important role in the development of Civil Aviation as well as the specialty of Aerospace Medicine and became a president of the American Medical Association. In 1939, building on the foundation established by Dr. Bauer, Dr. Harry Armstrong authored his first edition of *The Principles and Practice of Aviation Medicine*. As Dr. Armstrong's career progressed in the Army Air Corp: from laboratory commander, to General Officer, to Commander of the School of Aviation Medicine culminating as the Air Force Surgeon General—his textbook progressed from the second to the third editions. His next book carried a new title in 1961 reflecting the growing interest of "man in space" and was edited by Dr. Armstrong as he was joined by other contributors to *Aerospace Medicine*. The second edition, the mantle for editing which fell to Dr. Hugh Randel, a flight surgeon and Preventive Medicine Specialist, was published in 1971.

In 1980 as I departed the Armstrong Aerospace Medical Research Laboratory at Wright-Patterson to take command of the USAF School of Aerospace Medicine, a new edition was needed in response to the new research and developments in the field that had occurred during the past decade since the last textbook had appeared. Unfortunately, it was not possible to use the title introduced by Dr. Armstrong due to issues of clearing the copyright restrictions. Although Dr. Randel had visions of a third edition, he found he had neither the time nor the resources to proceed. At this point, it became necessary to change both the publisher and the title if the book was to continue, and I introduced *Fundamentals of Aerospace Medicine* and proceeded to identify other contributors who willingly joined in writing the chapters. This textbook was published in 1985 under my editorship. In 1996, the second edition followed with the third in 2002 jointly edited with Dr. Jeff Davis.

Now we go forward to this the fourth edition; time and circumstance combined with age and wisdom to place the challenge of editorship into younger and willing hands to move forward with the task. Dr. Davis had been requested to assist as co-editor of the third edition with the commitment to take on the responsibility of the fourth edition as I withdrew. This text is now in the hands of Dr. Davis and his co-editors.

The reader will quickly note that while military topics fade they are replaced with more contributions found on space medicine with commercial and general aviation holding their own. This reflects the changing allocation of research commitments in the United States. From the first edition of *Aviation Medicine* through the current fourth edition of "Fundamentals" the goal has not changed—to provide information on the physiology of flight, the hazards of flight, and the selection and health maintenance of those who fly and those who facilitate such activities.

New to this edition are chapters on Radiation, Toxicology, Emerging Infectious Disease, Dental, and Women's Health. The new section on the future discusses the governments' role in Aerospace and Commercial space activities.

This text is for the most part written from the perspective of the United States. This is not intended to be an international tome but it is anticipated that as with the prior editions other nations will find it useful. The audience has remained unaltered over time—physicians, physiologists, researchers, residents, and interested readers on the challenges to people in flight—whether in the terrestrial environment or the vastness of space.

This edition proves the merits of my decision to leave the stage for the next generation, and I thank readers for the kind words offered to the contributors and me for our best efforts.

Roy L. DeHart, MD, MPH, MS
Colonel and Chief Flight Surgeon, USAF (Ret)
Professor and Medical Director, Corporate Health Services
Vanderbilt University Medical Center

FOREWORD TO THIRD EDITION

This third edition of the already classic textbook *Fundamentals Of Aerospace Medicine* reflects and covers in detail contemporary trends in the evolution of a fascinating medical discipline, which in many areas of the world has achieved the level of a postgraduate university specialty.

Aviation medicine (later on, by natural extension, Aerospace Medicine) started as an indispensable response to a need to regulate the presence of humankind in aviation in relation to operational safety. More recently its scope has been broadened globally by giving emphasis to its *preventive* aspect; greater attention is additionally given to *all occupants* of air and spacecraft, including passengers and space tourists. The magnitude of global air transportation of healthy and less well passengers established the need to have a continuous update of knowledge of operational and environmental conditions (potentially) affecting humans. Such need is of paramount importance and this edition includes the most current information available in contemporary Aerospace Medicine.

Humans have adjusted their biological systems to life at or near sea level where they function at a given barometric pressure and a given partial pressure of oxygen with a normal hemoglobin range. Departure from this environment to altitude brings about the need to have adaptation mechanisms, which encompass ventilatory, circulatory and hematological adjustments over time.

Exposure to altitude conditions by aviation is almost immediate and does not allow the time for adaptation mechanism to appear, therefore technological aids are indispensable and as such, a classical example is given by cabin pressurization systems.

Proper interaction of humans, machines and environments is needed to achieve an optimum level of Operational Safety. Emphasizing again the need for proper interaction, we should remember that humans are necessary for the design, operation and maintenance of aircraft.

Every year, almost one quarter of the world's population travel by air on scheduled flights with an optimum level of safety compared to other means of mass transportation. In trying to satisfy the needs of the traveling public, experts are working hard in providing solutions to problems, or even better in preventing the appearance of those problems. Our specialty, a significant contributor to such level of safety, has seen a significant evolution of well defined and documented periods: its beginnings were empirical and were followed by observational, experimental, human factors and ergonomic stages. More recently the legal implications attracted the attention of the experts and, in this respect, more studies are being conducted in jurisprudence and ethics before an aeromedical decision takes place.

Over the years, aviation and medical authorities realized that research was needed and studies began to assess human performance and limitations related to aerospace environments and a need arose for a more precise definition of the objective of the specialty.

In relation to civil aviation, most of these studies were conducted at national levels; it soon became apparent that to achieve proper international standardization, medical requirements for aviation duties had to be adopted by an International Organization of the United Nations System, namely the International Civil Aviation Organization.

These requirements were incorporated in Annex 1 to the Chicago Convention and they include physical, mental, hearing, visual and color perception requirements. As a result of these standards and recommendations and their evaluation in the context of flight safety, it became indispensable to further study in detail the proper assessment of human performance, limitations and the consequences of exceeding those limitations.

Paraphrasing two sentences of General Howard W. Unger's foreword to the first edition of this textbook, it is worthwhile to emphasize that the specialty of Aerospace Medicine reflects a dynamic and progressive nature and that the need to openly share the wealth of information gathered is readily apparent.

Several definitions of Aerospace Medicine are available to readers; it seems indispensable to emphasize that, as far as crew members are concerned, it should be viewed as a multidisciplinary specialty related to *valid mental and physical requirements* in response to *realistic operational needs* to properly perform duties with an optimum level of safety. Related to passengers, clinical and environmental aspects are significant in order to achieve a good level of safety, health, comfort and well being.

Summarizing, it is indispensable for practitioners of Aerospace Medicine to continuously assess the adequate interaction needed between humans, machines and environments. Therefore, this edition of *Fundamentals of Aerospace Medicine* provides information and references useful to the medical examiners as well as to specialists in all aspects of the discipline. The wealth of information presented in this third edition allows practitioners, specialists and researchers to acquire it in a very well organized presentation. Such acquisition will allow us to have optimum exchanges of views and to perform duties in line with the requirements.

Silvio Finkelstein, MD, MSc
Former Senior Official, International Civil Aviation Organization
Past President, International Academy of Aviation and Space Medicine

FOREWORD TO SECOND EDITION

In introducing this impressive volume, I believe it most important to begin with a definition of the subject. *Aerospace medicine is that specialty area of medicine concerned with the determination and maintenance of the health, safety, and performance of those who fly in the air or in space.* This specialty is necessary because such flight subjects humans, with their earth-bound anatomy, physiology and psychology, to the *hostile* environment of air and space. Humans must adapt to or be protected from the changes in total environment pressure, reduced partial pressures of vital gasses, accelerative forces of flight, and changes in gravitational forces, to name just a few of the hazards encountered in flight.

Historically, the early balloon flights in the late 1700's produced reports of physical effects on the humans engaged in such ascents, but they were treated as interesting physiological observations. The advent of powered flight 92 years later by the Wright brothers on December 17, 1903 and then human spaceflight by Gagarin on April 12, 1961 revealed additional effects and potential obstacles to human performance in this new environment. However, these obstacles were viewed as challenges to be solved by those individuals supporting the explorers of these environments. They learned that the environments of air and space were a continuum and that basic physiologic fundamentals applied throughout this continuum. It is these environmental and vehicular stresses upon those who fly that are of ultimate concern to the aerospace medicine specialist.

The specialty area of aerospace medicine is young compared to some other medical specialties. Even though physicians had supported those who flew from the beginning, the specialty was not recognized until 1953. Though relatively young, aerospace medical research and extensive operational experience has been accumulated and well documented. These dates are in numerous scientific journals, reports, and books.

Specialized knowledge in many medical as well as non-medical areas is required of the practitioner of aerospace medicine. The medical specialties of otolaryngology, ophthalmology, cardiology, neurology, psychiatry/psychology, and pathology are of particular importance. The human cannot be separated from the vehicle, therefore certain engineering principles are also important. The total support of those who fly becomes a team effort. The aerospace medicine specialist must be able to communicate with other specialists. He or she must be able to gather all of this information and evaluate its impact on the health status of the pilot, relate this to the flying environment, and render a decision regarding fitness for flying. Therefore, the *Fundamentals of Aerospace Medicine* must cover a large amount of information. Aerospace medicine is of necessity very dynamic. It must keep pace with the ever-increasing technology of both medicine and aviation. Increases in fighter aircraft capabilities have forced a re-evaluation of a physiologic problem once thought to be solved. Current social assaults on the necessity of physical standards for those who fly have even forced a re-evaluation of medical standards. Aircraft are getting larger, and faster, and more and more people are flying. Such dynamic changes indicated the necessity for a current, comprehensive text. Dr. DeHart built upon the efforts of his predecessors, such as General Harry Armstrong, in gathering material for the first edition of *Fundamentals of Aerospace Medicine*. In the second edition, he has assembled the aid of respected authorities in their individual areas to add new chapter, update others with recent data and completely rewrite others.

We must understand our past if we are not to repeat the errors of the past. The section "Aerospace Medicine in Perspective" covers some of this important history very well. The sections "Physiology of the Flight Environment," "Clinical Practice of Aerospace Medicine" and "Operational Aerospace Medicine," have chapters providing fundamentals with basic references. The section "Impact of the Aerospace Industry on Community Health" includes a chapter concerning transmission of disease by aircraft with current concerns about an old and nearly forgotten nemesis, tuberculosis. Fundamentals revisited again. New chapters have appropriately been added: "Thermal Stress," "International Aviation Medicine" and "Management of Human Resources in Air Transport Operations."

It is the rare individual today who does not have some contact with the aviation environment in some manner. All physicians should have some basic knowledge of aerospace medical problems they or their patients might experience, as well as understand the breadth of knowledge possessed by the specialist in aerospace medicine. This text can serve as the basis of this knowledge for the general physician, the aerospace medicine specialist, the student, or anyone dealing with the medical support of military, general, or airline aviation, spaceflight, or the aerospace industry.

It has been my privilege in 45 years of practice in Aerospace Medicine to participate in the Air Force, NASA, and civilian areas. I congratulate Dr. DeHart and his authors for their excellent coverage of all these areas. If we adhere to the fundamentals and provide proper aerospace medical support, the human will continue to be able to adapt to zero gravity and re-adapt to earth's gravity with ever longer sojourns in space. I believe we will see many of earth's inhabitants experiencing spaceflight and even one day living in far flung space stations and colonies. The fundamentals will be the basic knowledge and the stepping stones making such progress possible. This knowledge must be used by the planners, designers, operators, and participants in achieving safe flight. This volume makes that knowledge available.

Charles A. Berry, MD, MPH
President, Preventive & Aerospace Medicine Consultants, P.A.
Past President, Aerospace Medical Association
Past President, International Academy of Aviation and Space Medicine
Past President, University of Texas Health Science Center in Houston, Texas
Former Director of Life Sciences—NASA

FOREWORD TO FIRST EDITION

This textbook reflects the dynamic and progressive nature of the specialty of aerospace medicine. The aviation industry has been explosive in development since the early 1900s, and the rapid advances in powered flight in military and civilian aviation have demanded the development of parallel medical systems to serve those who fly. The technologic advances that have occurred and continue to occur make it possible to move crews, passengers, troops, patients, and cargo far beyond all earlier expectations of time, size, weight, and distance. Although aviation has proven to be an important and increasingly rapid mode of transportation, it also has provided new methods of warfare and manned exploration beyond our planet.

Over the years, as the aviation industry grew, the stresses associated with flight, such as acceleration, speed, and altitude, became increasingly apparent. Historic events resulting from the progressive expansion of the flight environment were steadily being catalogued. The necessity for research to study and explore the physiologic effects imposed on man were recognized and vigorously pursued. Although research into the effects of unpowered balloon flights was important, the frequency and magnitude of the stresses associated with powered flight increased the urgency and sophistication of research efforts.

World War I provided the impetus for concerted educational and investigative efforts in the field of aviation medicine. Early in that war, human factors problems were strongly suspected as being the cause of many aircraft accidents and deaths. A school to train physicians to care for flyers and a medical research laboratory to consider urgent problems were established by the United States Air Service at Hazelhurst Field, Mineola, New York in 1917. Initial efforts to reduce the number of accidents and the loss of human life centered on good health and the application of more rigid physical standards for pilots and other aircrew members. The first class of "flight surgeons" graduated in 1918. A precipitous decrease in accidents and deaths was the direct result of these dedicated efforts. Since that time, flight surgeons have been intimately associated with flyers and their health and safety. As the list of medical responsibilities expanded, the industrial hygiene aspects of the developing industry included ground operations as well as the aerial mission. The school and laboratory at Hazelhurst Field moved a number of times and in 1959 finally arrived at its present location at Brooks Air Force Base, San Antonio, Texas. The institution is now known as the United States Air Force School of Aerospace Medicine.

Almost from the beginning of aviation medicine as a career field, it became apparent that a team effort was necessary so that an organized, multidisciplinary approach could be best applied to the problems associated with flight. Physicians, physiologists, psychologists, veterinarians, nurses, dentists, and other scientists covering many diverse skills and interests now contribute much time and effort to the men and women associated with flying.

Although much of the emphasis initially was of a military nature, the civilian aspects of aviation grew by leaps and bounds, and today there is a dedicated, cooperative, worldwide military-civilian career field. Additional schools and laboratories are now devoted to the collection of scientific data and the dissemination of vital information.

Typical of those involved in aviation or aerospace medicine has been the need and response to share openly the wealth of information being gathered. The complex and diverse data have been discussed by medical scientists of many nations at meetings and conferences. Periodicals and textbooks also have been very helpful in documenting and disseminating the knowledge that has accumulated. This text is a collection of the literary contributions of more than 40 authors representing the broad spectrum of aerospace medicine. Each contributor is a recognized expert among the many who practice within the specialty. These contributors are continuing a tradition begun over 50 years ago by Dr. Louis H. Bauer, who laid the first foundation stones with his text *Aviation Medicine*. Dr. Bauer's work has been expanded by the contributions of Dr. Harry Armstrong and, most recently by Dr. Hugh W. Randal. Thus, this text holds to the tradition of enumerating the basic principles of the challenging field of aerospace medicine. This book will be both a practical text for the student and most valuable reference source for the practitioner of aerospace medicine.

Howard W. Unger, MD
Major General, USAF, MC (retired)
Past President of the Aerospace Medical Association
Former Trustee of the American Board of Preventive Medicine

PREFACE

Twenty-five years ago, it was decided to revive the tradition of Dr. Armstrong and edit a new textbook for the discipline of aerospace medicine. This fourth edition of *Fundamentals of Aerospace Medicine* continues the legacy of Dr. Roy DeHart who had the vision to develop this textbook many years ago. We are indebted to his many years of service and volunteer hours for the first three editions, and to his foresight to recruit a new editor for the third edition. Dr. Roy DeHart trained a new generation of editors, and the field will always be indebted to him for his selfless service. Three new section editors were added for this edition, and the efforts of Dr. Robert Johnson, Dr. Jan Stepanek, and Dr. Jennifer Fogarty were critical to the scope and timeliness of this text. There are many returning contributors from the third edition, as well as many new chapters and new contributors. This fourth edition reflects the tremendous pace of change in that two chapters are devoted to the future at the dawn of the commercial space flight industry.

In the last 25 years, many changes have occurred in spaceflight and the pace of change has accelerated. The Space Shuttle first flew in 1981 and its planned retirement is on the horizon for 2010. The Mir Space Station was deorbited and replaced by the International Space Station (ISS) with the active participation by five international partners including the US, Russia, Japan, Canada, and the European Space Agency. Since the third edition, a second Space Shuttle accident resulted in the loss of *Columbia* and her crew of seven; the ISS was sustained using Russian Soyuz and Progress launches; and the first teacher in space flew completing the journey from the *Challenger* accident. Space Flight Participants pay to visit the ISS, and commercial space firms emerged after Space Ship One won the Ansari X-Prize. Various firms plan both suborbital and orbital space flights. Aerospace medicine practitioners of tomorrow may conduct medical exams for many interested passengers.

Commercial aviation continues to expand with the first flights of long-range, fuel-efficient aircraft substantially built from composite materials. Large aircraft have flown capable of carrying 550+ passengers. Both new types of aircraft may enter service in 2008. These new aircraft, and the development of a global economy and travel, increase the potential for transmitting disease quickly around the Earth. New challenges to global public health are recognized by the international aviation authorities with sustained planning efforts. In the US, the sport pilot certificate may stimulate the general aviation industry.

Military aviation continues to be driven by speed, agility, and survivability. New aircraft with vectored thrust provide variable acceleration environments with new challenges to human performance. The need to adapt to the ever increasing stressors of flight has forced scientists and aviation system designers to be ever more innovative in protecting the combat pilot. Chapters in this edition address not only advances in crew systems protection but issues of human factors in flight operational environments. Unmanned Aerial Vehicles are now commonplace and the unique challenges of these flights are addressed in the chapter of human factors.

The goal of the contributors to this edition is unchanged from a generation ago when the first edition was prepared for those physicians providing professional care and advice to general aviation pilots, for the specialist in aerospace medicine supporting the airline industry, the Department of Defense and the National Aeronautics and Space Administration, and now the emerging commercial space flight industry. The text is intended for students, residents, and perhaps many medical practitioners that may become more involved with global public health issues as well as medical exams for commercial space flight. The text is not intended to be a treatise on every subject introduced but rather a general review of the major topics that comprise the practice of aerospace medicine. The interested reader is provided with suggested readings and references to continue learning beyond the scope of this text.

The reader will find many new chapters in this edition including chapters devoted to toxicology, radiation, dental, women's health, unique aircraft, and commercial space flight. Substantial rewrites have been undertaken of many of the chapters from the third edition making this a substantially different text from the third edition. The pace of change is so great that planning is already underway for techniques to make new information available as soon as possible to the practitioner.

As has been the case in the three preceding editions, proceeds from this text will be distributed to schools and scholarship programs, nationally and internationally, that educate and train physicians in the field of aerospace medicine.

ACKNOWLEDGMENTS

As I mentioned in the preface, the current generation of practitioners of aerospace medicine owe a debt of gratitude to Dr. Roy DeHart who had the vision and determination to initiate Fundamentals of Aerospace Medicine some twenty-five years ago. I owe Dr. DeHart a heartfelt thank-you for allowing me to become an editor of the third edition, and to learn from him the complex process of assembling a text from content to contributors. Dr. DeHart not only revived this textbook with the first edition, but also insured its future by providing for new editors. His legacy to the field of aerospace medicine has many components, but this textbook may be the most significant in perpetuating the field. To Dr. Roy DeHart, thank you from the entire aerospace medicine community.

For the fourth edition, I too brought new editors to the textbook. We decided to divide the book into sections of physiology, clinical aerospace medicine, and operations, and I chose a section editor for each. I am indebted to the hard work and many hours that these new editors contributed, Dr. Jennifer Fogarty (physiology), Dr. Jan Stepanek (clinical aerospace medicine), and Dr. Robert Johnson (operations). Dr. Bob Johnson also helped with the logistics of the textbook, organizing conference calls and notes to authors. Ms. Diane Ellison at the University of Texas Medical Branch also helped with many of the textbook conference calls, letters, e-mails, and phone calls while preparing the book. This textbook was truly a team effort, and they all put forth an outstanding effort and countless hours of time in editing and assembling this text.

I want to recognize the contributors who are the authors who wrote this volume. Without their technical expertise, willingness to volunteer many hours of research, writing and revisions, this textbook would not exist. As a community of aerospace medicine practitioners, we owe a debt of gratitude to these authors without whom the underlying research, clinical evaluations, and operational experience would not exist to be able to sustain the field. In all aspects of practice, in operations, research, clinical medicine, and teaching, there are many competing demands for time, and less recognition of the value of an academic effort to one's home organization. So to the contributors and all of their outstanding technical contributions and volunteer efforts, one last grateful thank-you.

There is a great deal of new material in this textbook as rapid developments are now occurring in aerospace. New opportunities are emerging in suborbital and orbital commercial space flight, and there are plans for commercial flights to the moon. These new developments should produce new practice opportunities for the aerospace medicine practitioner, and the future is as bright as perhaps at any time in the history of the field. By the time of the fifth edition, I hope we can look back on the successful flight of hundreds if not thousands of space flight participants on suborbital and orbital flights.

It has been a pleasure to work with the Lippincott Williams & Wilkins staff, and the assistance of Ms. Kerry Barrett, Senior Managing Editor, was invaluable to the success of this edition. She was always available for sound advice, by email or phone, and would provide timely assistance to the editors and contributors. She also saw the value of the timing of this fourth edition with the rapid changes in aerospace including long-range and large commercial aircraft, global public health issues, the expansion of government space programs to include space flight participants, the emergence of an exploration program, and the rapid development of the commercial space flight industry. As Dr. DeHart noted in the third edition, Williams and Wilkins was the publisher of the original aviation medicine text, edited by Dr. Harry G. Armstrong, and the tradition most definitely continues.

To you the next generation of practitioners, I hope this text gives you the foundation for success in aerospace medicine, and encourages you to become the next generation of practitioners, researchers, and teachers essential to the success of this field. I hope you enjoy the field as much as I have, and find the time to pass along your expertise to the next generation.

Jeffrey R. Davis

CONTRIBUTORS

Richard Allnutt, MD, MPH, MS(EE)
Biodynamic Research Corporation
San Antonio, Texas

Arnold A. Angelici, Jr., MD, MS
Occupational Medicine
Federal Aviation Administration
Civil Aerospace Medical Institute
Oklahoma City, Oklahoma

Melchor J. Antuñano, MD, MS
Clinical Associate Professor
Department of Preventive Medicine and Community Health
University of Texas Medical Branch
Galveston, Texas;
Director
Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, Oklahoma

Michael Bagshaw, MB, FFOM, DAvMed
Program Director Aviation Medicine
School of Biomedical & Health Sciences
King's College London
Guy's Campus
London, UK

Denise L. Baisden, MD, MS
Assistant Regional Flight Surgeon
Southwest Region
Federal Aviation Administration
Oklahoma City, Oklahoma

Robert D. Banks, BEng, MD
Principal Consultant
Biodynamic Research Corporation
San Antonio, Texas

Michael R. Barratt, MD, MS
Physician/Astronaut
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Stephen A. Bernstein, MD, MPH, FAAFP, COL, MC, SFS
Director, US Army Aeromedical Activity
US Army
Enterprise, Alabama

James W. Brinkley, BS
Former Director
Human Effectiveness Directorate
Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio

Stephen L. Carpenter, MD
Medical Officer,
Aerospace Medical Certification Division
Federal Aviation Administration
Oklahoma City, Oklahoma

John W. Castellani, MD
Research Physiologist
Thermal and Mountain Medicine
USARIEM
Natick, Massachusetts

Samuel N. Cheuvront, MD
Research Physiologist
Thermal and Mountain Medicine Division
U.S. Army Research Institute of Environmental Medicine
Natick, Massachusetts

Thomas F. Clarke, MD, MPH
Director General Preventive Medicine Residency
USAF School of Aerospace Medicine
Brooks City Base, Texas

Curtiss B. Cook, MD, FACP
Lieutenant Colonel
Professor of Medicine, Division of Endocrinology
Mayo Clinic College of Medicine
Scottsdale, Arizona

Paula A. Corrigan, MD
Branch Chief
Department of Internal Medicine
Aeromedical Consult Service
USAF School of Aerospace Medicine
Brooks City Base, Texas

Francis A. Cucinotta, MD
Chief Scientist
NASA Space Radiation Program
Lyndon B. Johnson Space Center
Houston, Texas

Jeffrey R. Davis, MD, MS
Professor, Preventive Medicine and Community Health
University of Texas Medical Branch
Galveston, Texas

Roy L. DeHart, MD, MS, MPH
Professor and Director
Vanderbilt Center for Occupational and Environmental Medicine
Nashville, Tennessee

J. Robert Dille, MD, MIH
Consultant in Aerospace Medicine
Norman, Oklahoma

David F. Dinges, PhD
Professor and Chief
Division of Sleep and Chronobiology,
Department of Psychiatry, and Center for Sleep and Respiratory Neurobiology
University of Pennsylvania School of Medicine
Philadelphia, Pennsylvania

R. Key Dismukes, PhD
Chief Scientist for AeroSpace Human Factors
NASA Ames Research Center
Moffett Field, California

W. R. Ercoline, MS, PhD
Manager, San Antonio Operations
Life Sciences Group
Wyle Laboratories
San Antonio, Texas

Nils Erikson, MD, MPH
Captain, U.S. Navy, Medical Corps
Director, Aerospace Medicine Residency
Naval Operational Medicine Institute
Pensacola, Florida

Jennifer A. Fogarty, PhD
Adjunct Assistant Professor
Preventive Medicine and Community Health
University of Texas Medical Branch
Galveston, Texas;
Biomedical Risk Coordinator
Space Medicine Division
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Namni Goel, PhD
Assistant Professor
Division of Sleep and Chronobiology,
Department of Psychiatry, and Center for Sleep and Respiratory Neurobiology
University of Pennsylvania School of Medicine
Philadelphia, Pennsylvania

Jerry R. Goodman, MS
Manager, Acoustics Office and Lead ISS Acoustics
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Monica B. Gorbandt, MD
Consultant, U.S. Army School of Aviation Medicine
Medical Boards/Aviation Medicine
Fox Army Health Center
Redstone Arsenal, Alabama

David P. Gradwell, PhD, MB, ChB
Whittingham Professor of Aviation Medicine
Faculty of Occupational Medicine
Royal College of Physicians
St.AndrewsPlace
London, UK;
Consultant Adviser in Aviation Medicine (RAF)
Aviation Medicine Wing
RAF Centre of Aviation Medicine
Henlow, Bedfordshire, United Kingdom

Gary W. Gray, MD, PhD, FRCP (C)
Consultant in Medicine
Canadian Forces Environmental Medical Establishment
Defence Research and Development Canada
Toronto, Canada

Ferdinand W. Grosveld, MS, PhD
Consultant
Hampton, Virginia

Richard M. Harding, BSc, MBBS, PhD
Principal Consultant
Biodynamic Research Corporation
San Antonio, Texas

John D. Hastings, MD
Senior Consultant in Neurology
Federation Aviation Administration
Tulsa, Oklahoma

Steven M. Hetrick, MD, MPH
Director, Occupational Medicine Program
Department of Graduate Education
USAF School of Aerospace Medicine
San Antonio, Texas

Jeffrey Hudson, PhD
Biomedical Scientist for General Dynamics
Wright-Patterson Air Force Base, Ohio

Douglas J. Ivan, MD
Chief Aerospace Ophthalmology
Branch,
USAF School of Aerospace Medicine
Brooks Air Force Base, Texas

John T. James, PhD
Chief Toxicologist
Habitability and Environmental Factors Division
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Richard T. Jennings, MD, MS
Associate Professor and Director
Aerospace Medicine Residency
University of Texas Medical Branch
Galveston, Texas

Robert Johnson, MD, MPH, MBA
Associate Professor of Medicine
Preventive Medicine and Community Health;
The University of Texas Medical Branch
Staff Physician
Aviation Medical Center
University of Texas Medical Branch University Hospitals
Galveston, Texas

David R. Jones, MD, MPH
Consultant in Aerospace Psychiatry
Montgomery, Alabama

Robert W. Kenefick, MS, PhD, FACSM
Research Physiologist
Thermal and Mountain Medicine Division
United States Army Research Institute of Environmental Medicine
Natick, Massachusetts

James A. King, MD, COL, USAF, MC, FS
Chief, Emergency Medical Department
Wilford Hall USAF Medical Center
San Antonio, Texas

Richard A. Knittig, MD, MPH
Aerospace Medicine Consultant
Naval Aerospace Medical Institute
Pensacola, Florida

William B. Kruyer, MD
Chief Cardiologist
Aeromedical Consultation Service
USAF School of Aerospace Medicine
Brooks City-Base, Texas

James Perry Locke, MD, MS
Flight Surgeon
Flight Medicine
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Cheryl Lowry, MD, MPH LT COL, USAF, MC, FS
Misawa Air Force Base, Japan

Gregory J. Martin, MD
Director, Infectious Diseases Clinical Research Program
Associate Professor of Medicine & Preventive Medicine
Uniformed Services University
Bethesda, Maryland

P. Vernon McDonald, PhD
Director, Commercial Human Spaceflight
Wyle Laboratories Inc.
Houston, Texas

Kerry McGuire
University of Wisconsin Doctoral Student
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Glenn W. Mitchell, MD, MPH
Vice-President for Clinical Safety
Sisters of Mercy Health System
St Louis, Missouri

Stanley R. Mohler, MD, MA
Professor Emeritus
Aerospace Medicine
Boonshoft School of Medicine
Wright State University
Dayton, Ohio

William M. Morlang, II, DDS
Associate Professor
Department of Oral and Maxillofacial Pathology
School of Dental Medicine
Tufts University
Boston, Massachusetts;
Consultant in Forensic Dentistry
Armed Forces Medical Examiner
Armed Forces Insitute of Pathology
Washington, DC

David M. Musson, MD, PhD
Assistant Professor
Department of Anesthesia Academic Director, Center for Clinical Simulation McMaster
University
Hamilton, Ontario, Canada

Catherine O'Brien, MS
Research Biologist
Thermal and Mountain Medicine Division
US Army Research Institute of Environmental Medicine
Natick, Massachusetts

Robert R. Orford, MD, CM, MS, MPH
Assistant Professor
Division of Preventive, Occupational, and Aerospace Medicine,
Department of Internal Medicine
Mayo Clinic
Scottsdale, Arizona

A. J. Parmet, MD, MPH, FACPM, FAsMA, AIAASM
Instructor
Viterbi School of Engineering/Aviation Safety & Security
University of Southern California
Los Angeles, California;
Employee Health
Department of Internal Medicine
Saint Luke's Hospital of Kansas City
Kansas City, Missouri

James R. Phelan, MD
Assistant Clinical Professor
Preventive Medicine and Community Health
University of Texas Medical Branch
Galveston Texas

Shean E. Phelps, MD, MPH, FAAFP
Chief, Injury Biomechanics Branch
US Army Aeromedical Research Laboratory
Ort Rucker, Alabama

Jeb S. Pickard, MD, FCCP
Staff Pulmonologist
Aeromedical Consultation Service
USAF School of Aerospace Medicine
Brooks City-Base, Texas

Duane L. Pierson, PhD
Microbiologist
Habitability and Environmental Factors Division
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Thomas Rathjen
Chief, Habitability and Environmental Factors Division
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Eduard M. Ricaurte, MD, MS
Research Physician
Federal Aviation Administration
Civil Aerospace Medical Institute
Oklahoma City, Oklahoma

Elizabeth E. Richard, MBA
Strategist
Wyle Laboratories, Inc.
Houston, Texas

Charles F. Sawin, PhD
Associate Director, Space and Life Sciences
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Warren S. Silberman, DO
Manager, Aeromedical Certification Division
Federal Aviation Administration
Civil Aeromedical Institute

Suzanne D. Smith, PhD
Senior Research Engineer
Human Effectiveness Directorate
Biosciences and Protection Division
United States Air Force
Wright-Patterson Air Force Base, Ohio

John A. Smyrski III, MD, MPH, MBA
Lieutenant Colonel
Medical Corps, Senior Flight Surgeon
Aerospace Medicine and Family Medicine;
Staff Physician
Division Surgeon
US Army: 25th Infantry Division, Schofield Barracks, Hawaii and Tripler Army Medical
Center
Honolulu, Hawaii

Jan Stepanek, MPH, MD
Assistant Professor of Medicine
College of Medicine;
Medical Director, Aerospace Medicine Program
Divison of Preventive, Occupational and Aerospace Medicine
Department of Internal Medicine
Mayo Clinic
Scottsdale, Arizona;
Assistant Professor
Preventive Medicine and Community Health
The University of Texas Medical Branch
Galveston, Texas

James R. Strader, Jr., MD
Staff Cardiologist
Aeromedical Consultation Service
USAF School of Aerospace Medicine
Brooks City-Base, Texas

Claude Thibeault, MD
Clinical Associate Professor
Department of Preventive and Community Health
University of Texas Medical Branch
Galveston, Texas

Thomas J. Tredici, MD
Senior Scientist
Aerospace Ophthalmology Branch
USAF School of Aerospace Medicine
Brooks Air Force Base, Texas

Anthony P. Tvaryanas, Maj, USAF, MC, FS
Chief, UAS Human Systems Integration
Brooks City-Base, Texas

James M. Vanderploeg, MD, MPH
Program Manager
Wyle Laboratories
Houston, Texas

Stephen J. H. Véronneau MD, MS
Research Medical Officer
Aerospace Medical Research Division
FAA Civil Aerospace Medical Institute
Oklahoma City, Oklahoma

Dougal B. Watson, MBBS, BSc
Principal Medical Officer
Civil Aviation Authority
Petone, New Zealand

James T. Webb, MS, PhD
Consultant
Aerospace Physiology
USAF School of Aerospace Medicine
San Antonio, Texas

Mihriban Whitmore, PhD
Manager, Usability Testing and Analysis Facility
Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas

Kenneth A. Williams, MD, FACEP
Director, University Emergency Medicine Foundation
Rhode Island Hospital
Providence, Rhode Island

Kevin W. Williams, PhD
Research Psychologist
Human Factors Laboratory
FAA Civil Aerospace Medical Institute
Oklahoma City, Oklahoma

Richard S. Williams
Chief Health and Medical Officer
NASA
Washington, DC

Gregory Zehner
Senior Anthropologist, Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio

CONTENTS

CLINICAL

OPERATIONS

ABBREVIATIONS

17-OHCS 17-hydroxy corticosteroid
a acceleration
A anterior
AA aeronautical adaptability
AA/NA Alcoholics/Narcotics Anonymous
$AaDO_2$ alveolar/arterial oxygen difference
AAMA Army Aeromedical Activity
AART Aircraft Accident Research Team
AC aberrant conduction
ACAP Aeromedical Consultants Advisory Panel
ACC Air Combat Command (formerly TAC)
ACES advanced concept ejection seat or advanced crew escape suit
ACGIH American Conference of Governmental Industrial Hygienists
ACLS advanced cardiac life support
ACM aerial combat maneuver
AE aeromedical evacuation
AFB Air Force Base
AFMIC Armed Forces Medical Intelligence Center
AFRL Air Force Research Laboratory
AFSS automated flight service stations
AG artificial gravity
AGARD Advisory Group for Aerospace Research and Development
AGSM anti-g straining maneuver
AHI apnea-hypoxia index
AL arbitrary limit
ALJ Administrative Law Judge
A-LOC almost loss of consciousness
ALPA Airline Pilots Association
AM Aerospace Medicine
AMAK airway medical accessory kit
AMCD Aeromedical Certification Division
AMDA Airline Medical Directors Association
AME aviation medical examiner
AMIP Aircraft Mishap Investigation and Prevention
AMP Aerospace Medical Professional
ANDES Aircraft Noise Design Effects Study
ANPRM advanced notice of proposed rule making
ANR active noise reduction
ANSI American National Standards Institute
AOPA Aircraft Owner's and Pilot's Association
APA Aviation Medical Physician Assistants
API Aviation Preflight Indoctrination
APS accident prevention specialist
APU auxiliary power unit
AR aortic regurgitation
AR advisory report
ARMA Adaptability Rating for Military Aeronautics
ARTCC Air Route Traffic Control Centers
AS aortic stenosis
ASHRAE American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASI Italian Space Agency
ASR automatic speech recognition
ATA atmospheres absolute
ATAGS advanced technology anti-G suite
ATCS air traffic control specialists
ATCT air traffic control towers
ATLS advanced trauma life support
ATM air traffic management
ATP air transport pilot
AV atrioventricular
BAD bipolar affective disorder
BAV bicuspid aortic valve
BEI biological exposure indices
BNC balanced noise criteria
bpm beats per minute
BPT bronchial provocation test
BTPS body temperature, pressure saturated
BV blood volume
BW bacteriological warfare
C cervical vertebra
C^3 Command, Control and Communications
CABG coronary artery bypass graft
CAD coronary artery disease
CAF coronary artery fluoroscopy
CAMI Civil Aeromedical Institute
CCAT Critical Core Air Transport
CCK contaminant clean-up kit
CERAP combined enroute and approach center
CFC chlorofluorocarbons
CFIT controlled flight into terrain
CG center of gravity
CHeCS Crew Health Care System
CLL central light loss
CMO crew medical officer
CMS countermeasures system
CNS central nervous system
CO cardiac output
CO carbon monoxide

CO_2 carbon dioxide
COPD chronic obstructive pulmonary disease
CPAP continuous positive airway pressure
CPAP continuous positive pressure assisted breathing
CPK creatine phosphokinase
CRM crew resource management
CRV crew return vehicle
CSA Canadian Space Agency
CSD cortical spreading depression
CSF cerebral spinal fluid
CT computed tomography
CTT color threshold test
CTV crew transport vehicle
CVP central venous pressure
CW chemical warfare
d specific density of blood
DAET Department of Aviation Medicine Education and Training
DAI diffuse axonal injury
DARA Deutsche Agentur fur Raumfahrtangelenheiten
dB decibel
DCIEM Canadian Defense and Civil Institute of Environmental Medicine
DCS decompression sickness
DEXA dual energy x-ray absorptiometry
DL_{CO} diffusing capacity, carbon monoxide
DLW doubly labeled water
DMORT Disaster Mortuary Operational Response Team
DNBI disease and/or non-battle injury
DO dissolved oxygen
DoD Department of Defense
DOT Department of Transportation
DRT Diagnostic Rhyme Test
DS dead space, lung
DSM IV Diagnostic and Statistical Manual of Mental Disorder, Fourth edition
DLR Germany's Aerospace Research Center and Space Agency
E epinephrine
EBCT electron beam computed tomography
ECG electrocardiogram or graph
ECLSS environmental control and life support system
ECT equivalent chill temperature
EDO extended duration orbiter
EEG electroencephalogram or graph
EFIS electronic flight information systems
EHS environmental health system
EMK emergency medical kit
EMU extravehicular maneuvering unit or extravehicular mobility unit
ENEV(Canada) estimated no effects value
EOG electrooculography
EPT effective performance time
ERV expiratory reserve volume
ESA European Space Agency
ESP erholungspulssume (sum of heart beats)
ET effective temperature
EVA extravehicular activity
F force
FAA Federal Aviation Administration
FAR Federal Aviation Regulations
FDPB fatigue–decreased proficiency boundary
FEF_{50} forced expiratory flow at 50%
FEV_1 forced expiratory volume at 1 second
FFS Frank's flying anti-G suit
FFT fast Fourier transformation
FLIR forward looking infrared
FM frequency modulation
FoF fear of flying
FRC functional reserve capacity
FS flight surgeon(s)
FSDO Flight Service District Office
g gravitational constant of 9.81 m/sec^2
G acceleration-induced inertial force
GCR galactic cosmic radiation
GE gastric emptying
GERD gastroesophageal reflux disorder
GHz giga Hertz
G-LOC G-induced loss of consciousness
GMO General Medical Officer
GOR gradual onset rate
GPS global positioning system
GWP global warming potential
$+G_x$ positive transverse G (A to P)
$+G_z$ positive vertical G
$\pm G_y$ positive/negative lateral (side to side)
$-G_x$ negative transverse G (P to A)
$-G_z$ negative vertical G
h blood column height (mm)
+H hydrogen ion
HALO high-altitude, low-opening
HBO hyperbaric medicine
HCM hypertropic cardiomyopathy
HEEDS helicopter emergency egress device
HEMA hydroxyethylmethacrylate
HEPA High-efficiency particulate air
HFACS Human Factors Analysis and Classification System
HGP hard gas permeable (lenses)
HIMS Human Intervention Motivation Survey
HMD helmet mounted display
HMO health maintenance organization
HMS health maintenance system
HR heart rate (beats per minute)
HSG high sustained G
HSP health stabilization program
HTG high-G tolerance group
HUT head-up tilt table
Hz Hertz

I inspired
IAM Institute of Aviation Medicine
IATA International Air Transport Association
IC inspiratory capacity
ICAO International Civil Aviation Organization
IEEE Institute of Electrical and Electronics Engineers
IGF-I Insulin-like growth factor I
IHR International Health Regulations
ILD interstitial lung disease
IMS Integrated Medical System
INR international normalized ratios
IP International Partners
IRB Institutional Review Board
ISO International Standards Organization
ISS International Space Station
IVCD intraventricular conduction delay
JAA (Europe) Joint Aviation Authorities
JSC Johnson Space Center
K constant of 1 G tolerance increase
km kilometer
kPa kilopascal
KSC Kennedy Space Center
KW kilowatt
L-1 type of AGSM
LAD left axis deviation
LAHB left anterior hemiblock
LAMPS light airborne multipurpose system
LASIK laser in-situ keratomileusis
LBBB left bundle branch block
LBNP lower body negative pressure
LCG liquid cooling garment
LDH lactate dehydrogenase
LEO low earth orbit
LEP laser eye protection
LEQ equivalent continuous noise
LES launch and entry suits
LiOH lithium hydroxide
LOC loss of consciousness
LOS line of sight
LSAH Longitudinal Study of Astronaut Health
LTG low-G tolerance group
LVH left ventricular hypertrophy
m mass or meter
m/s velocity: meters/second
m/s^2 acceleration: $meters/second^2$
M-1 Maneuver number 1; a type of AGSM
MAK medical accessory kit
MBK medication and bandage kit
MCC Mission Control Center
MCCH Mission Control Center Houston
MCV mean corpuscular volume
MEDEVAC aeromedical evacuation
MEDOP Medical Extended Duration Orbiter Pack
MEF Marine Expeditionary Force
MFB Multifunctional Battalions
mg milligrams
MHz MegaHertz
MI myocardial infarction
MMFR mid-maximal expiratory flow rate
mm Hg mm mercury
MMIS Military Man-In-Space
MOOTW military operations other than war
MPH Master of Public Health
MPSR multipurpose support room
MR mitral regurgitation
MRI magnetic resonance imaging
MRT modified rhyme test
MS mitral stenosis
MS multiple sclerosis
MSE mental status evaluation
MSLT multiple sleep latency testing
MVP mitral valve prolapse
MW milliwatt
MWT maintenance of wakefulness testing
NAA not aeronautically adaptable
NAIMS National Airspace System Information Monitoring System
NAMI Naval Aerospace Medical Institute
NAMRL Naval Aeromedical Research Laboratory
NAS Naval Air Station
NAS National Airspace System
NASA National Aeronautics and Space Administration
NASDA National Space Development Agency of Japan
NATO North Atlantic Treaty Organization
NAWC Naval Air Warfare Center
NBC Nuclear, Biological and Chemical
NC noise criteria
NCRP National Council on Radiation Protection
NE norepinephrine
NIR nonionizing radiation
No. 14CFR Title 14 of the Code of Federal Regulations
NORAD North American Air Defense Command
NOx oxides of nitrogen
NPRM Notice of Proposed Rule Making
NRR noise reduction rating
NSAID nonsteroidal anti-inflammatory drug
NTSB National Transportation Safety Board
NVG night vision goggles
O_2 oxygen
OBS operational bioinstrumentation system
OOM on-orbit maintenance task allocation
OSA obstructive sleep apnea
OSAPL overall sound pressure level
OSHA Occupational Safety and Health Administration
OTC over-the-counter
P posterior or pressure
Pa Pascal
P_a arterial blood pressure (mm Hg)
P_A pulmonary alveolar pressure

PAC premature atrial contraction
P_{ACO_2} arteria0l CO_2 partial pressure
P_{AO_2} alveolar oxygen tension
P_{AO_2} arterial oxygen partial pressure
PB phonetically balanced
PBG positive pressure breathing during G exposure
PCM primary care manager
PDAY pathobiological determinants of atherosclerosis of youth
PEFR peak expiratory flow rate
PET positron emission tomography
PFT pulmonary function test
P_H hydrostatic pressure (mm Hg)
PLL peripheral light loss
PMC private medical conference
PMMA polymethyline-thacrylate
PMR proportionate mortality ratio
PN perceived noisiness
PO_2 oxygen partial pressure
PP partial pressure
PPB positive pressure breathing
PPG positive pressure "g" protection
PRK photorefractive keratectomy
PSD power spectral density
PSG polysomnography
PSI pounds per square inch
psi pounds of pressure per square inch
psig pounds of pressure per square inch - gas
PSP primary spontaneous pneumothorax
PTA posttraumatic amnesia
PTCA percutaneous transluminal angioplasty
PTS permanent threshold shift
PTSD posttraumatic stress disorder
PVC premature ventricular contraction
Q blood perfusion rate
RAD right axis deviation
RAF Royal Air Force
RAM Residency in Aerospace Medicine
RBBB right bundle branch block
RBC red blood cell
RBCM red blood cell mass
RCB reduced comfort boundary
REM rapid eye movement
RF radio frequency
RFS Regional Flight Surgeon
RK radial keratotomy
ROR rapid onset rate
RQ respiratory quotient
RSA Russian Space Agency
RSC Russian System of Countermeasures
RSS recumbent seating system
RTFS returned to flying status
RTLS return-to-launch site
RV residual volume
SNR signal to noise ratio
S_a arterial oxygen saturation
SACM simulated aerial combat maneuver
SEE shuttle emergency eyewash kit
SGOT serum glutamic-oxaloacetic transaminase
SII speech intelligibility index
SIL speech interference levels
SLT signal light test
SMAC space maximum allowable concentration
SMO Senior Medical Officer
SMR standardized mortality rate
SMS space motion sickness
SODA Statement of Demonstrated Ability
SOMS shuttle orbiter medical systems
SOs oxides of sulfa
SPE(s) solar particle events
SR sweat rate
SSRI serotonin specific uptake inhibitors
STI speech transmission index
STPD standard temperature, pressure, dry
STS significant threshold shift or Space Transportation System
SVOC semi-volatile organic compound(s)
TAC Tactical Air Command
TAL transoceanic abort landing
TBI traumatic brain injury
TCCS trace contaminant control system
TCD transcranial Doppler
TCP tri-cresyl phosphate
TEE total energy expenditure
TGA transient global amnesia
TLC total lung capacity
TLV threshold limit value
TLV total lung volume
TRACON terminal radar control center
TTS temporary threshold shift
TUC time of useful consciousness
TV tidal volume
TWA time weighted average
UAV unrestricted aerial vehicles
UK United Kingdom
URLs universal resource locators
USAAF United States Army Air Force
USAF United States Air Force
USAFSAM United States Air Force School of Aerospace Medicine
USASAM United States Army School of Aviation Medicine
USN United States Navy
V pulmonary ventilation rate
$\dot{V}/\dot{Q}$ ventilation–perfusion ratio
VC vital capacity
VHMs voluntary head movements
VOC volatile organic compound(s)
VOR vestibulo-ocular reflex
VR venous return

VT ventricular tachycardia
VTG volume thoracic gas
VTOL vertical take off and landing
W watt
w weight
WBGT wet bulb globe temperature
WCS (shuttle) waste collection system
WHO World Health Organization
WPW Wolff-Parkinson-White syndrome
WWII World War II

CHAPTER 1

The Beginnings: Past and Present

J. Robert Dille and Stanley R. Mohler

Thus do men serve history and history the ages.

—Eddie Rickenbacker

History started today, not only yesterday.

—Anon.

EARLIEST CONCEPTUALIZATIONS

As prehistoric people made grueling trips across trackless lands, they surely must have envied the swift, graceful, and seemingly effortless flight of birds. Fantasies and legends involving wings and flight by gods, angels, rulers, and guardians occur in the folklore of nearly every culture. Windmills, kites, parachutes, and the rocket (the latter from China where gunpowder was invented about 900 AD) were early inventions bearing upon the pursuit of human flight.

The legend of father and son, Daedalus and Icarus, states that they made wings of feathers held together by wax to escape from King Minos' Crete. During escape, Icarus ignored Daedalus' admonishments, and flew too near the sun: the wax melted and he fell into the sea.

Roger Bacon, a 13th century Franciscan monk, was quoted as hearing about artificial wings that turned about a sitting person and beat the air "after the manner of a flying bird."

Leonardo da Vinci designed a parachute in 1500. He also drew pictures of hypothetical human-powered helicopter and ornithopter flying machines. Leonardo died in 1519 AD, and his approximately 500 pages of notes and 1,500 sketches were forgotten for more than 300 years.

If available earlier, these writings could possibly have accelerated the course of aeronautical development.

Many legends, figures, and fantasies attest to our early predecessors' fascination with the possibilities of human flight, an achievement that awaited the coalescence of intuition, technologic advances, and goal-driven experimentation. Of course, human tolerances to higher altitudes and in-flight acceleration forces awaited actual flight experiences before awareness of these aspects arose. In addition, the need for occupant restraint systems, crashworthiness protection, and a means to deal with in-flight spatial disorientation under conditions of loss of outside visual reference, also awaited flight experience.

The general sequence of topics in this chapter proceeds from the earliest conceptualizations by century, flowing through the 16th century. This latter European "Age of Reason" launched the 17th century "Age of Enlightenment." Topics to be covered include the aeromedical implications of the first "mountain sickness" reports along with early laboratory gas studies and the hypoxic experiences of balloonists. The December 17, 1903 first flight of a heavier-than-air powered aircraft piloted by the Wright Brothers launched the basis for an explosive growth of aviation and the need for medical support of aviators. The April 12, 1961 earth-orbiting flight of Yuri Gagarin, of the Union of Soviet Socialist Republics (USSR), opened the era of human space flight.

The chapter concludes citing the development of space medicine, bringing us to the July 20, 1969 Apollo 11 moon landing by the National Aeronautics and Space Administration (NASA). The moon landing was conducted by Neil Armstrong and Edwin Aldrin Jr., the first two humans to walk on a heavenly body other than the earth, while Michael Collins, their orbiting Command Module Pilot circled overhead.

SIXTEENTH CENTURY EXPERIENCES

Discomfort with mountain travel was documented after the Spanish army under Cortez attacked Mexico in 1519. In addition, the Spanish army under Pizarro experienced mountain sickness 25 years later while conquering areas subsequently known as *Ecuador, Chile*, and *Peru*.

Later in the century, Jesuit Father Jose de Acosta blamed the air of lofty places. On five crossings over the Andes, he noted a loss of appetite, the presence of nausea and abdominal pain, in addition to vomiting of food, phlegm, bile, and blood. Father Acosta had profound weakness and had to be supported on his horse; he also had dizziness and was panting. Upon return to lower altitude, the symptoms shortly disappeared.

Acosta wrote "Not only men feel this, animals do too, and sometimes stop so that no spur can make them advance." Acosta was "convinced that the element of the air is in this place so thin and so delicate that it is not proportioned to human breathing which requires it denser and more temperate."

Acosta's account was published in Seville in 1590 but is best found in the Hitchcock (1) translation of *Bert's Barometric Pressure*. The book, originally published in French in 1878, contains 264 references on mountain sickness. Scientific studies on the effects, prevention, and treatment of acute and chronic mountain (altitude) sickness, pulmonary edema, and cerebral edema have been conducted in the Andes, on Mt. McKinley, and in the Himalayas. Scientists who conducted this research included McFarland, Hurtado, Hultgren, and Krakauer.

SEVENTEENTH AND EIGHTEENTH CENTURY PROGRESS

Evangelista Torricelli (1608–1647), an Italian physicist, invented the mercury barometer 50 years after Acosta's observations. He studied the response of small animals to vacuum. Otto von Guericke (1602–1686), engineer, of Germany, invented the pneumatic pump in 1672. He studied how candle flames were extinguished, animals could not live, and sounds would not travel under vacuum. He also showed that horses could not pull apart two vacuum-containing hemispheres. Robert Boyle (1627–1691), Irish natural philosopher, observed bubbles in the eye of a viper following its decompression in a vacuum environment. He discovered that at a constant temperature the volume of gas varies inversely with pressure—the famous "Boyle's Law."

Joseph Priestly (1733–1804), English scientist, and Antoine Lavoisier (1743–1794), French chemist, are separately credited with discovering oxygen.

During 1783, brothers Joseph and Etienne Montgolfier of France successfully launched hot air balloons, using burning damp straw, wool, and occasionally old shoes and even old meat in the mix. A rooster, a duck, and a sheep were hefted by hot air on September 19 of that year. On October 15, the brothers lifted Pilatre de Rozier, an apothecary of Metz, in a tethered hot air balloon to a height of 50 ft. On November 23, de Rozier and Francois Laurent Marquis d'Arlandes were free floated across Paris in a hot air balloon. American ambassador to France, Benjamin Franklin, observed that these developments in ballooning foretold a promising future.

Professor Jacques Alexandre Cesar Charles (1746–1823), along with Joseph Louis Gay-Lussac (1778–1850), articulated what is now known as *Charles' Law* that states "At a constant pressure, a given amount of gas will expand its volume in direct proportion to the absolute temperature." Charles invented the hydrogen balloon in 1783 and made a flight on December 1 with a companion (the balloon's maker). After the companion left the balloon after a 1-hour 45-minute flight, the lightened balloon immediately rose to an altitude of 3,048 m (10,000 ft). Charles reported right ear and maxillary pain with increasing altitude, and this report is usually considered the first case of aerotitis. Early in the next century, Gay-Lussac made a balloon flight, on September 16, 1804, to an altitude of over 7,016 m (23,000 ft), a record that stood for approximately a half century.

Trained in Scotland and loyal to King George III, Boston physician John Jeffries moved to London at the beginning of the Revolutionary War. He, along with crowds estimated at 150,000 to 250,000, gathered to observe balloon ascents by John Pierre Blanchard and the Italian, Vincent Lunardi. Jeffries paid Blanchard 100 guineas to fly from London to Kent in a hydrogen balloon. On the flight, Jeffries carried a thermometer, barometer, pocket electrometer, hydrometer, precision timepiece, compass, small telescope, and seven sealed vials to collect air samples at different altitudes for Henry Cavendish, the discoverer of hydrogen. The results were reported to the Royal Society.

Blanchard had announced his intention to fly across the English Channel before agreeing to take Jeffries along. Again, Jeffries agreed to pay the expenses of the flight, and, if necessary to save Blanchard, he would jump into the channel.

Blanchard, in a bit of deviousness, ordered a vest lined with lead to keep the balloon from lifting, forcing Jeffries out. The tailor mistakenly sent the vest to Dr. Jeffries at a hotel in Dover, and the ruse was uncovered. On January 7, 1785, the two were the first to cross the English Channel, and Jeffries became the first paying aerial passenger on an international flight.

They carried the first over-water survival gear, cork vests, and equipment required during the over-water flight. Jeffries reported visual illusions: "we were fixed and objects appeared to pass to or from us or revolve around us." He also reported that "we were enveloped by a certain stillness that could be felt" (possibly sensory deprivation). At one point it was almost necessary for Jeffries to jump into the water. Later, close to a hard landing, most of their clothing, the celebration bottle of brandy, the life vests, and all equipment except the barometer, were jettisoned.

To soften the landing in France, Jeffries thought to eliminate "five to six pounds of urine." A letter from Benjamin Franklin's son in London, to his son who was with his grandfather in Paris was delivered, the first airmailed letter.

Jeffries' accounts have been reprinted in *Aviation, Space, and Environmental Medicine* (2,3).

In 1789, Dr. Jeffries returned to Boston and practiced medicine until his death in 1819. He was active in teaching, and gave the first public lecture on anatomy. He was a founder of the Boston Medical Library.

Jeffries helped Blanchard to make the first hydrogen balloon free flight in America on January 9, 1793. This event occurred in Philadelphia with the departure from the yard of the Walnut Street prison. A large crowd observed the departing flight, including President George Washington and the French Ambassador. Washington gave Blanchard a letter of introduction (Blanchard's English was not very good, hence the letter for those he may meet on landing—some consider this the first U.S. passport). Blanchard's pulse rate data collected for Dr. Benjamin Rush was 84 beats/minute on the ground and 92 at 1,772 m (5,812 ft). Six air samples were collected for Dr. Casper Wistar.

The balloon landed in Gloucester County, New Jersey. Blanchard returned to Europe and made a number of flights in various countries. While flying over The Hague, Netherlands, he is reported to have had an in-flight heart attack, falling more than 50 ft. He died on March 7, 1809, the first pilot in command to have an in-flight incapacitating cardiac event.

On June 15, 1785, Pilatre de Rozier, the first person lifted by the Montgolfiers, accompanied by a companion, Pierre Romain, attempted to cross the channel from France to Britain in a combination hydrogen–hot air balloon. The hydrogen caught fire half an hour after take-off and both died in the accident, the first aeronautic fatalities. De Rozier's fiancée, Susan Dyer, witnessed the explosion, collapsed, and died.

THE NINETEENTH CENTURY

A Belgian physicist, Etienne Robertson, ascended to approximately 7,000 m (22,966 ft) with a music teacher named Lhoest, at Hamburg, Germany, on July 18, 1803. He described a hurried pulse, mental and physical apathy, and an indifference instead of his usual glory and passion for discoveries. He reported that his lips had swelled from blood rushing there and his hat seemed too small. He was able to place his hand in boiling water without feeling pain. He flew with Russia's first aeronaut, Sacharoff, on June 30, 1804.

Robertson's son, Eugene, ascended to 6,000 m (21,000 ft) at Castle Garden, New York, on October 16, 1826.

Dr. Claude Bernard (1813–1878) of France is considered the founder of experimental medicine. He studied the effects of illness, carbon dioxide, cold, and superoxygenated air on hypoxia tolerance. He studied carbon monoxide combination with hemoglobin as a cause of oxygen starvation. While studying the liver, he discovered that liver glycogen (he gave the substance its name) broke down to glucose, elucidating the glucose–glycogen relationship.

Paul Bert (1833–1886), considered by some to be the father of aviation medicine, was born in Auxerre, Yonne, France. He was trained in engineering, law, physiology, and medicine. He succeeded his mentor, Claude Bernard, to the chair of physiology, Faculte' des Sciences, Paris. He conducted extensive work in the early 1870s, the latter culminating in his classic book, *La Pression Barométrique, Recherches de Physiologie Expérimentale* in 1878. Mary Alice and Fred Hitchcock translated the volume into English during World War II.

Bert undertook studies to explain the symptoms reported by aeronauts during their balloon ascensions. He conducted 670 experiments in bell jars and an altitude chamber of his construction. He used plants, sparrows, rabbits, guinea pigs, cats, dogs, and humans, and reported the findings in his book. He established that death occurred at a partial pressure of oxygen of 35 mm Hg, irrespective of atmospheric pressure. He found that the intermittent inhalation of air rich in oxygen relieved symptoms of hypoxia. He also recognized that excess carbonic acid in the blood and tissues created adverse effects. The hazard of loss of too much carbon dioxide through hyperventilation was apparently not recognized. Bert died as Resident General, Tonkin province, French Indochina, at age 53, on November 11, 1886, during an attack of dysentery.

James Glaisher (1809–1903) and his balloon engineer, Henry Coxwell (1819–1900), made several ascents to high altitudes over England to relatively high altitudes without supplemental oxygen. On September 5, 1862, reaching 8,839 m (29,000 ft), Glaisher was unconscious for an estimated 7 minutes. It is reported that the two balloonists experienced some acclimatization to high altitudes without turning blue or having difficulty breathing.

Henri Sivel, a naval officer, and Joseph Croce-Spinelli, a journalist, ascended on March 22, 1874, in the balloon, Polar Star, to a height of 7,300 m (23, 950 ft). They carried bags provided by Bert containing 40% and 70% oxygen, the former to be breathed on reachi ng 3,600 m (11,811 ft) and the latter on reaching 6,000 m (19,685 ft). It was observed that the oxygen improved strength, alertness, memory, visual acuity, and appetite.

On April 15, 1875, they, along with a third aeronaut, Gaston Tissandier, launched in the balloon, Zenith, with goldbeater's bags (made from the cecum of an ox) of 65% and 70% oxygen. They sought to reach an altitude well above 8,000 m (26,246 ft), exceeding Glaisher's and Coxwell's September 5, 1862 record. Bert sent a message that the French balloonists did not have sufficient oxygen, but they had lifted off before the arrival of the message. At 7,450 m (24, 442 ft) they cut three bags of ballast, probably in a state of hypoxic euphoria, and climbed to an estimated 8,600 m (28, 215 ft). All three lost consciousness and Sivel and Croce-Spinelli died in-flight. Tissandier passed out, coming to some time later as the balloon had spontaneously descended to a lower altitude and struck the ground.

In the third edition of his *Principles and Practice of Aviation Medicine* (4), Armstrong wrote, "the first use of air transportation in support of medical activities occurred during the Siege of Paris in 1870 when a total of 160 patients were removed from the city by means of an observation balloon." Lam has examined the records and found that no passengers were patients (5). The records contain the names of the balloonists, the weights of the mail, and the landing sites. The flights occurred between September 23, 1870 and January 21, 1871, during the Paris siege as the Franco-Prussian war continued. Tissandier was one of the balloonists but most were sailors.

TWENTIETH CENTURY: EXPONENTIAL GROWTH OF AEROSPACE MEDICINE

The invention of the practical heavier-than-air powered and controlled flight by Wilbur and Orville Wright of Dayton, Ohio, initially proved by them on December 17, 1903 at Kitty Hawk, North Carolina, was followed in the years before World War I by flight schools and derivative aircraft in all parts of the world. Large dirigibles also evolved, and the German Naval Airship Division conducted air raids over London, flying at 5,000 to 6,000 m (16,400–20,000 ft) whenever possible to avoid airplane attacks. Eight hours of cold, hypoxia, and engine noise caused documented dizziness, tinnitus, headache, increased heart and respiration rates, and fatigue. The supplied compressed oxygen had an unpleasant oily taste. Crewmembers and commanders were reluctant to use oxygen, despite symptoms, because to do so was considered as a sign of weakness. Liquid oxygen was later used because more could be carried, weight for weight, than as a gas (4).

On February 7, 1912, the U.S. War Department published instructions concerning the physical examination for candidates with respect to aviation duties. These instructions were preceded by the 1910 minimum medical standards for military pilots that were developed in Germany, the first country to establish such standards. Soon afterward, the Italian Air Medical Service followed suit. The French and British established military pilot medical standards in 1912. The U.S. military established detailed physical standards for aviators under the guidance of Theodore C. Lyster in 1916. These were published in 1919 as the *Air Service Medical* (6).

With respect to the early standards, the British emphasized cardiovascular performance and hypoxia tolerance with a rebreather bag that progressively decreased the oxygen to simulate the decrease in oxygen pressure at higher altitudes. The French added vestibular function and neurovascular steadiness in the presence of an unexpected gunshot. The Italians emphasized reaction time. When the United States acquired its first airplane in 1908, the general army duty medical standards applied. These emphasized the dental characteristics, a holdover from the Civil War era when enlisted men needed to be able to pull a cork by the teeth from a powder flask. The 1912 draft aviation medical standards emphasized normal vision, normal hearing and eardrums, and the visual ability to determine distances. Disqualification included colorblindness, acute or chronic disease of the middle or inner ear, or auditory nerve, or any disease of the respiratory, circulatory, or nervous system. Equilibrium was tested by standing with the eyes closed, and then hopping with the eyes open and then closed. In 1914 new arbitrary, more rigorous standards, were ordered by the Surgeon General, but failure rates were so high for new young applicant officers that the standards were relaxed. One screening test involved the candidate holding a needle between the thumb and forefinger. A blank pistol was fired behind the candidate's head. If the startle reaction produced blood, the candidate was disqualified.

During the first year of flying in World War I, when there was little combat, the English and French found that 2% of aircraft accidents were due to combat, 8% were due to mechanical problems, and 90% were due to human failure; two thirds of these 90% were reported to be due to physical defects (6).

The U.S. medical personnel thought that a considerable proportion of the physical defects leading to accidents "are the immediate or late effects of strain on the circulation under the influence of low oxygen tension in the air" (6). Some soldiers disqualified for further combat because of battle fatigue, shell shock, and neurocirculatory asthenia became pilots. The Royal Air Force (RAF) of the United Kingdom started a Care of Flyer Service. This activity reduced pilot deficiency accidents over 2 years from 60% to 12%. Improved physical standards, examinations, flight training, and attention to physical and emotional problems undoubtedly contributed to this decline.

Even so, many aces had physical defects that would be disqualifying by current standards. Roy Brown, who shot down top ace Baron Manfred von Richthofen (80 victories) in 1918, had chronic stomach distress, requiring the regular consumption of soda, milk, and brandy. American pilot Elliott Springs (5 victories) consumed milk of magnesia and gin, alternately, to relieve chronic stomach symptoms. "Eddie" Rickenbacker (26 victories) required a mastoidectomy during the war. French "ace of aces," Georges Guynemer (53 victories) disappeared during a flight that was preceded by emotional strain and a crash-induced concussion and knee injury.

A little-known pilot with the name of Veil, when asked why he stayed with the Lafayette Flying Corps when the United States came into the war, stated that he would not qualify in the U.S. air arm because he had "a game leg, a stiff neck, a hole in my groin, and a blood disease among other things."

Britain's top ace, 34-year-old Mike Mannock (73 victories) was nearly blind in the left eye from a congenital condition. American William Thaw (5 victories), Lafayette Escadrille and later U.S. 103rd Aero Squadron, had normal vision in only one eye. Lt. Frank Alberry of Australia lost his right leg in ground combat in 1916. He was determined to fly as he could not be a ground troop with an artificial leg. He sought an audience with the King, and obtained a letter of acceptance. He took this to the Air Board, went through pilot training, and shot down seven enemy aircraft. In 1921, the New Australian Air Force would not accept him for flight service.

German ace Oswald Boelcke (40 victories), had severe asthmatic attacks and Georg Zeumer, skilled pilot and 1915 combat instructor of Baron von Richthofen, was a "lunger" with advanced tuberculosis, chronic coughing, and a very unhealthy appearance. Flying was considered a seated sedentary activity, a factor in the decisions to allow certain soldiers too impaired to be in the trenches to take to the air.

The U.S. Army had issued orders forbidding hard landings and the wearing of spurs in the cockpit. In May 1917, the Army established new medical standards for flight crew, including normal eye muscle balance, fusion, intraocular tension, visual field, near-vision accommodation, and the ability to clear the ears on descent. A turning chair test took the place of the stand, walk, and hop test. Specially trained physicians at 35 centers in the United States conducted the examinations.

Theodore C. Lyster, MD, Chief Surgeon of the U.S. Army Aviation Section, selected in May 1917 Isaac H. Jones, MD, a Philadelphia otologist, to open the first of the 35 medical examination centers at the University of Pennsylvania Hospital. In December, Dr. Lyster and Dr. Jones spent 3 months in Europe, assessing the medical problems facing aviators. On return, they established the Air Service Medical Research Laboratory at Hazelhurst Field, Mineola, Long Island, New York. William H. Wilmer, MD was put in charge. This new facility contained a low-pressure chamber, allowing the program to conduct pioneering studies in aviation physiology aspects and aircrew protection from hypoxia.

The above-mentioned principals established a medical research board on October 18, 1917 to investigate conditions that affect the efficiency of pilots, to carry out tests on pilot abilities to fly at high altitudes, to carry out tests on suitable equipment to supply oxygen to pilots, and to act as a standing medical board on matters relating to the physical fitness of pilots. Examination procedures and research at the laboratory are provided in *Air Service Medical* (6).

A program at the new laboratory instituted selection and training measures for new aeromedical examiners. Isaac Jones, MD, and fellow otologist, Eugene R. Lewis, MD, recommended that the examiners fly regularly. Lewis introduced the new term for these physicians, *flight surgeons*. Pilots and commanding officers were to be counseled with respect to an airman's condition that warranted temporary or permanent "grounding."

The first flight surgeon to report for active duty at a U.S. base was Capt. Robert J. Hunter. From Park Field, Tennessee, Dr. Hunter submitted a report dated May 13, 1918 to Dr. Lyster documenting early efforts to reduce accidents. The report stated that 63 candidates were interviewed, a sick call was held on May 27, a rest period was established between 11:00 AM and 3:00 PM, and athletic and recreation exercises were to be held twice/week. Sanitary cups in the field and shady areas for cadets were instituted. Three nonfatal accidents were investigated, one due to inexperience, one possibly due to hitting the head on the cowl during a loop, and one due to chasing a crow. Discussions with the mess officer were undertaken. Hunter acted as a member of a special board in several cases to consider whether further instruction of certain cadets should be continued.

Dr. Isaac Jones believed that the doctor who flies best understands the pilot. He taught that keeping pilots mentally and physically fit to continue flying was the main purpose of flight surgeons. He reportedly said that it might take 100 years to convince pilots not to feel that the main purpose of flight surgeons is to find a way to not let pilots fly. Jones and Lewis probably coauthored *Air Service Medical* and Jones also wrote *Equilibrium and Vertigo*, 1918. Raymond E. Longacre, MD, a 1921 graduate of the new flight surgeon school, developed for the first time a set of personality criteria for selecting candidates for flight training. Following World War I, Hazelhurst Field was converted to a private airport (Roosevelt Field), and the medical research facility was moved in 1919 to nearby Mitchel Field. In 1926 the facility again moved, this time to Brooks Field, San Antonio. Later it moved to Randolph Field and subsequently back to Brooks.

In 1924, the *National Geographic Magazine* stated, "Perhaps the most heroic test of an aviator's grit and stamina is an altitude climb" (7). Rudolph W. "Shorty" Schroeder of McCook Field, Dayton, Ohio, began to set altitude records in 1918, reaching 10,093 m (33,114 ft) on February 27, 1920, his third record. He used a LePere LUSAC-11 (LePere U.S. Army Combat) open cockpit American-produced two-seat biplane that resembled the British Bristol fighter. It had a GE Moss supercharger powered by exhaust gases to boost air to its 400 hp Liberty engine. Schroeder's oxygen gave out at the peak altitude and he lost consciousness. He recovered at 914.4 m (3,000 ft) after losing 9,144 m (30,000 ft) in 2 minutes and landed at the edge of the river near McCook Field. There were other problems, including ice in the oxygen tubes and carbon monoxide. The flight was a major demonstration of capabilities and deficiencies in pursuing high-altitude flights.

John A. Macready followed the Schroeder flights in the same aircraft and reached 11,521 m (37,800 ft) on September 28, 1921. He wore suits of woolen underwear, his regulation uniform, a knitted wool garment, a leather suit padded with down and feathers, fur-lined gloves, fleece-lined moccasins over the boots, and goggles treated with an antifreeze gelatin (Figure 1-1). An oxygen tube was attached to a pipestem mouthpiece. A mask protected the face from freezing at the −67°F range of air temperature.

Macready and Oakley Kelly made the first nonstop transcontinental airplane flight in a Fokker T-2 monoplane across the United States, departing Roosevelt Field, Long Island, New York, at 12:36 PM (EST) on May 2, 1923, and landing at Rockwell Field, San Diego, California, at 3:26 PM (EST) on May 3, a flight of 26 hours and 50 minutes covering 2,516 mi. The pilots had made two prior "endurance" cross-country flights in the Fokker to test their physical capabilities on such long flights as well as the aircraft and its equipment. The pilot in the open cockpit just behind the engine could check the maps *en route* while the other pilot in the fuselage with side windows kept the wings level with a set of controls, a "human autopilot." Kelly made

FIGURE 1-1 Lt. John A. Macready, U.S. Army Engineering Division test pilot, McCook Field, Ohio, dressed for his record ascent to 11,521 m (37,800 ft) on September 28, 1921.

the take-off from Roosevelt Field and Macready made the landing at Rockwell Field. The pilot seat back was modified so that the two could change places periodically during the long flight.

Macready made the first night parachute jump when engine failure occurred at 518 m (1,700 ft) on June 18, 1924. He landed unhurt. He also set National Aeronautic Association altitude and duration records in a bomber in 1924, and reached 11,796 m (38,700 ft) in an XCO5 aircraft with a turbosupercharger on January 29, 1926. Some scientists in 1923 reportedly told Macready that he might cross a boundary beyond the pull of gravity and become a space satellite.

Lt. Harold R. Harris, Flying Section Chief, Engineering Division, McCook Field, set ten Federation Aeronautique Internationale (FAI) World Air Records and 16 American air records during October 1, 1920 and January 30, 1925. During June 1921, Harris flew the first pressurized aircraft, an experimental D-99-A single-engine biplane. Owing to the circumstance that the pressurization system capability greatly exceeded the outflow valve capability, with no pilot control of cabin pressure, the aircraft cabin became pressurized to 914 m (3,000 ft) below sea level as the aircraft climbed out. The cabin air became hot and Harris was fortunate to get the airplane unharmed on the ground. Much was learned from this experience.

On October 20, 1922, Harris was the first pilot to save his life by parachuting from a Loening PW-2A that broke up in the air (Figure 1-2). He was made member number one of the subsequently famous "caterpillar club," established by the Irvin Parachute Company.

Charles Lindbergh joined the Army as an aviator in training (note: he was already a low-time civilian pilot), Brooks Field, Texas. During training while diving on a target aircraft, another pilot ran into Lindbergh's craft, the two airplanes becoming locked with one another. Both pilots were in the first class to be issued parachutes, and both parachuted to safety. Lindbergh graduated in March 1925, at the top of his class. Army aviation was underfunded, so he left and joined the Missouri National Guard.

Lt. Albert Stevens, a skilled aerial photographer, often flying with Macready, parachuted from a Martin MB2 bomber from an altitude of 7,376 m (24,000 ft) to set a world record over McCook field on June 12, 1922.

Capt. Hawthorne C. Gray set unofficial balloon altitude records in 1927. On March 9, 1927, he rose from Belleville, Illinois to an altitude of 8,230 m (27,000 ft) where he passed out due to faulty oxygen equipment and overexertion from emptying ballast bags. Fortunately, the balloon descended and he lived to try again. On May 4, 1927, he lifted off with a new oxygen system and a cord to dump ballast, reaching 12,945 m (42,470 ft). On descent, the balloon began falling at an excessive rate, so he bailed out at 383 m (8,000 ft). Therefore, he did not qualify for an official FAI record, but he was alive. He reported that during the flight he experienced a feeling of detachment, severe chest pains on exertion, and a strong desire to take a nap. On November 4, 1927, Gray went aloft again, reaching 12,192 m (40,000 ft). Unfortunately, his clock froze, he exhausted his oxygen, lost consciousness, and died. On November 5, the gondola was found in a tree near Sparta, Tennessee. Scientists concluded that high-altitude balloon flights should be equipped with sealed cabins. Gen. James H. Doolittle stated during his speech on October 20, 1962, on the occasion of the dedication of the Federal Aviation Agency's Civil Aeromedical Research Institute new research facilities, Oklahoma City, Oklahoma, that "The price for almost every advancement in aviation has been high. Progress was frequently bought with someone's life."

McCook Field personnel undertook an agricultural in-flight spray program to eradicate the "catalpa sphinx moth" that was wiping out a grove of catalpa trees near Piqua, Ohio. The grove was 32 km (20 mi) north of McCook, and the wood from the trees was used for fence posts and poles. In cooperation with the Ohio Agriculture Experimental Station in Wooster, McCook personnel modified a JN6H (Jenny) to carry powdered arsenate of lead in hoppers that could be released during passes over the trees while flying at an altitude of 6 to 9 m (20 to 30 ft). The aircraft dispensed 79 kg (175 lb) of the insecticide during six passes of 9 seconds each while flying 129 kph (80 mph) on August 3, 1921. Millions of the moth larvae died from eating the dusted leaves.

FIGURE 1-2 The wreckage of a Loening PW-2A that broke up in the air, October 20, 1922. The pilot, Lt. Harold R. Harris, was the first U.S. Army Air Service flier to save his life by parachuting from his disabled aircraft.

McCook engineer, Etienne Dormoy designed the hopper, John A. Mcready flew the aircraft, and Albert W. Stevens flew alongside to document the dusting. Lt. Harold R. Harris left McCook in 1925 to help found the Huff-Daland crop dusting organization, the forerunner of Delta Airlines, the latter formed in the 1928 to 1929 period from the proceeds of the sale of the crop dusting company. Stevens, in cooperation with the U.S. Department of Agriculture, collected samples of plant disease spores at 10,972 m (36,000 ft) and subsequently at 22,066 m (72,395 ft) on November 11, 1935 using the Explorer II balloon. During 1926, aerial dusting was used by the marines at Quantico to kill mosquitoes (Figure 1-3). During the latter World War II period in the Pacific theatre, updated spraying techniques were used to kill mosquitoes and flies.

EARLY CRASH PROTECTION

The first fatal crash in powered aircraft activities occurred on September 17, 1908. Orville Wright was demonstrating for the U.S. Army their Wright Model A Flyer at Fort Myer, Virginia, with Lt. Thomas E. Selfridge as passenger. Following some in-flight maneuvers at 30.5 m (100 ft), a propeller fractured. Orville cut power but the propeller caught in the aircraft rigging and the craft crashed in a turn. Selfridge and Orville were extricated and taken to the Post medical facility. Selfridge died of a skull fracture. Orville had a fractured left femur, fractured ribs, and other skeletal injuries, but recovered to fly again, although he never completely healed and had lifelong discomfort. Following a repeat demonstration by Orville at Fort Myer in an improved

FIGURE 1-3 The Marine Corps fought a "battle to death with mosquitoes that besiege the Marine base at Quantico" in 1926 using a plane with a special emblem. Shown are MG Elie Cole, Capt. W.M. Garton, USN MC, and Col. T.C. Turner.

Model A Flyer, on July 30, 1909, the Army Signal Corps agreed to purchase the new aircraft on August 2, 1909. His passenger was Lt. Benjamin D. Foulois.

Lt. Henry H. (Hap) Arnold, later a General and Chief of the U.S. Army Air Forces during World War II, elected shortly after the 1908 Fort Myer accident to protect his head during flight by donning his college football helmet. Louis Bleriot, the first to fly the English Channel, on July 25, 1909, began installing restraint systems. Lt. Benjamin D. Foulois, later a U.S. Army Air Service General, wore a trunk strap while flying in San Antonio in 1910. He is quoted as saying ". . . to keep me in that damn seat during turbulence."

Hardy V. Wells, Royal Navy, wrote in 1913 that serious nonfatal injuries as well as fatal injuries could be avoided by having "some giving material in the position in front of the pilot where the head would strike" or by "a safety belt having shoulder straps" (8). His recommendation for elastic belts was not sound. During this time, some used the practice to release the belts just before landing, supposedly to prevent becoming trapped in an airplane that rolls over, catches fire, or prevent being crushed by a pusher-type engine.

French automobile builder M.G. Leveau patented in 1903 an automobile seat restraint system involving high-backed seats, lap belts, and adjustable chest cross-straps. Despite early technology, experiences and recommendations about impact protection, and estimates of 85% to 93% reductions in general aviation aircraft accident fatalities with upper torso restraint, decades would pass before general installation would occur.

The 1950s to 1960s research data produced and widely disseminated by John Stapp, John Swearingen, and others, gradually began to be applied by regulatory authorities with respect to civil aircraft as well as automobiles.

EARLY AIR AMBULANCE ACTIVITIES

In 1909, U.S. Army Capt. George H.R. Grosman, stationed at Fort Barrancas, Florida, conceived a heavier-than-air aircraft designed to carry patients. With Lt. Albert Rhodes, he designed, built, and flew such an aircraft. The War Department, still apprehensive from the purchase of the 1909 Wright aircraft, did not elect to acquire the air ambulance aircraft.

In 1914, Lieutenant Colonel Donegan, Royal Army Medical Corps (MC), proposed to transport medical staff, specialists, emergency equipment, and wounded by airplane. A shortage of aircraft precluded implementation. Captain R.H. Cordner, a year earlier, had recommended such an approach but the approach had been rejected as impractical.

FIGURE 1-4 Airlines were involved in early air ambulance service that existed in the United States, Sweden, and several other European countries in 1929.

In 1910, Marie Marvingt, a French surgical nurse, balloonist, and airplane pilot, proposed the development of airplane ambulances. In 1912, she ordered an airplane from the Deperdussin Company, but due to failure of the company, the craft was not delivered.

She served clandestinely as an infantry soldier in 1914, serving on the frontlines until her superiors discovered that she was a female. She found her way into aerial service, flying as a bomber pilot over Germany. For this, she earned the Croix de Guerre. Throughout the war, she continued to press for air ambulances.

Marie Marvingt developed a civil air ambulance service in 1934 for Morocco, with aircraft on skis for landing on desert sand. She was the first woman in France to be awarded the diploma of "Infirmiere de l'Air" (Flight Nurse) in 1935.

The first airplane air evacuation in history was from Albania and was carried out in November 1915 by the French Expeditionary Forces and Serbian pilots using French fighter aircraft. The French subsequently ordered aircraft suitable for forward evacuation.

In 1947, Italy was the only other country with this evacuation capability. The authorities elsewhere considered such air evacuation to be dangerous, medically unsound, and militarily impossible.

Marvingt's dream of airplane ambulances was fully realized during World War II. Military wounded evacuation numbers reached 1 million/year by the end of the war. Forward air evacuation of wounded soldiers was developed during the Korean War, and the establishment of air ambulances before the Vietnam war reduced the risk to the wounded of dying in combat in that war to less than half that experienced during World War II.

Colonial Flying Service offered the first known civilian air ambulance flying service in 1929. A Braniff Airline aircraft is shown in connection with an air ambulance operation in 1929 (Figure 1-4). Boeing Air Transport (predecessor of United Airlines) hired Ellen Church, a registered nurse, as a flight attendant in 1929, introducing a practice that United Airlines followed for some years. The cabin environment of the early unpressurized aircraft, flying in the lower turbulence-prone altitudes, resulted not infrequently in passenger illnesses, especially nausea, vomiting, dizziness, and middle ear discomfort and pain. Nurse flight attendants were especially beneficial in soothing and treating passengers who were so afflicted.

POST–WORLD WAR I AVIATION MEDICINE RESEARCH

The years between 1920 and 1935 saw aviation medicine research drop to a very low level. The World War I Air Service Medical Research Laboratory was abandoned in 1920. Longacre's 1923 selection criteria for candidates for flight training was a recognized accomplishment. In addition, Neely Mashburn's "automatic serial-action complex coordinator," (Figure 1-5) developed by May 1931

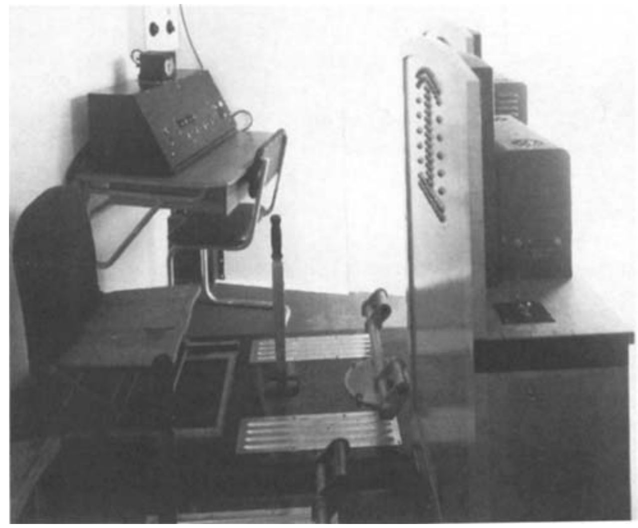


FIGURE 1-5 Mashburn's complex coordinator for determining aptitude for flying training was one of the most significant accomplishments in aviation medicine research between 1920 and 1935.

at the new School of Aviation Medicine (SAM), Randolph Field, Texas, was the most accurate single measure of pilot aptitude at the time. The device was used in World War II to determine reaction times related to pilot aptitude for selection purposes with respect to landing, alcohol effects, and possible age-related aspects. A third accomplishment was that of Dr. David A. Myers, a member of the first formal class of flight surgeons. He worked with William Ocker, a veteran pilot, who was an expert at using the gyroscopic turn and bank instrument developed by Elmer and Lawrence Sperry. He demonstrated through use of the Barany chair, a head-mounted view box, and a stick that the test subject could position to show if a sensation of turning existed, or not, and, if so, the direction of the perceived turn, that the inner ear would be confused in turns should external horizontal reference be lost (Figure 1-6). Ocker and Crane published their book, *Blind Flight in Theory and Practice* in 1936. Maj. General Harry G. Armstrong, United States Air Force (USAF), MC considered this work on spatial disorientation "the greatest contribution of medicine to the technical advancement of aviation" (9).

Two physicians led the revival of aviation medicine in the United States: Harry G. Armstrong and Louis H. Bauer. Between 1939 and 1952, Dr. Armstrong wrote three textbooks on aviation medicine and edited the first textbook on aerospace medicine. Dr. Bauer published a textbook on aviation medicine, 1926, that received attention on both sides of the Atlantic as was the case with Armstrong's publications (10).

Dr. Armstrong felt that flight surgeons were not fully trained until they had completed a 4-month basic course, had 3 years at an Air Corps station, and had 300 hours of flight time. Their duties included diagnosing and treating ailments and trauma cases, as well as performing physical examinations and caring for flyers, "the essence of aviation

FIGURE 1-6 A modification of the Barany turning chair has been used to demonstrate spatial disorientation that results from absence of a true horizon or instrument proficiency to tens of thousands of pilots in the United States.

medicine" according to Armstrong. In addition, the flight surgeons should continually investigate the effects of flight, and seek remedies for adverse environmental conditions.

Armstrong (born on February 17, 1899), De Smet, South Dakota, served as a private in the U.S. Marines during World War I. He attended the premedicine program at the University of Minnesota, and then the University of South Dakota's medical school, earning the Bachelor of Science in Medicine, 1923. He then matriculated to the University of Louisville, Kentucky, earning the MD degree in 1925. He entered private medical practice in Minneapolis, Minnesota. In 1929, he accepted a commission in the Army Reserve and was assigned to Brooks Field, San Antonio, where he enrolled in the aviation medicine course. A sergeant who was a proponent of dropping soldiers by parachute suggested that a doctor should make a parachute jump to provide a professional assessment of possible associated physiological and psychological problems. This was Armstrong's first research challenge. Armstrong is quoted by Mr. Bob MacNaughton in a U.S. Air Force News Release, Lackland Air Force Base, 19 May, 1981, as "So I made the jump and wrote it up. I told them nothing really happens except it really scares the hell out of you."

Armstrong, with the concurrence of his wife Mary, was offered and accepted a regular Army commission. Of course, he had to take lessons on riding horses the army way, and driving a six-mule ambulance. He was assigned in 1931 as flight surgeon to the First Pursuit Group, Selfridge Field, Michigan. His flying time was in Berliner Joyce P-16 two-seat fighter planes. During winter flying, he observed aircrew problems with frostbite and fogged goggles. He wrote to Maj. Gen. Malcolm C. Grow, medical chief of the Army Air Corps, with respect to pilot in-flight medical problems, and received orders on September 15, 1934 to assume the post of consultant to the engineering section, Wright Field. In May 1935, Armstrong succeeded in obtaining approval for the "Physiological Research Unit," later renamed the *Aeromedical Research Laboratory*. In June 1936, Armstrong persuaded John W. Heim, PhD, Harvard University, to join the new initiative at Wright Field. Heim and Armstrong proved to be a highly productive research team.

Armstrong instituted a series of research activities at Wright Field that included cold chamber studies with various protective clothing for flying (accomplished in the small altitude chamber that was moved from Mineola to Wright Field, and discovered by Armstrong to be underneath a trapdoor in his office), hypoxia altitude chamber studies accomplished in a new altitude chamber commissioned by Armstrong, oxygen mask studies, aeroembolism studies, barotrauma in regard to the middle ear and sinuses, and positive- and negative-G force accelerations using a centrifuge that he and Heim had put together. Additional Armstrong studies included developing a protocol for occupant protection during decompressions should the planned pressurized aircraft be developed.

Information on this subject was essentially nonexisting. Therefore, to collect data on this topic, Armstrong placed himself inside an 8-ft long tank that was 2.5 ft in diameter, sealed at ground level pressure. The tank had a series of cork-sealed holes of increasing size. The tank was within an altitude chamber, and, during a series of tests at the simulated altitude of 10,000 ft, Armstrong started by extracting the smallest cork, and progressively worked up to the largest. He reported not being hurt at any of the decompression levels.

Armstrong also served as the test subject on a sled that he had built, upon which was a simulated cockpit. He had shoulder harness straps added, started with low-speed impacts, worked up to higher speed impacts, and demonstrated that an individual's neck would not be broken by wearing shoulder harnesses under such conditions. This finding dispelled a contemporary myth slowing the acceptance of shoulder harnesses. He also studied helmet requirements for head injury protection during accidents.

In 1935, Armstrong made headlines in the Dayton papers by predicting that some day airplanes would fly as fast, or faster than, a 0.45-caliber bullet. Subsequently, on January 24, 1939, H. Lloyd Child power-dived a Curtiss Hawk H-75A-1 over Buffalo, New York, to 966 kph (600 mph) reaching Mach 0.813 at 2,790 m (9,000 ft) altitude. This was in excess of the speed of a black powder pistol bullet.

He also discovered resistance by some at SAM with respect to establishing a laboratory at Wright Field as he proposed. As he developed his first textbook, he met objections from SAM, the Commandant stating that this was the job of SAM.

Numerous reports published by Armstrong along with his associate, Heim, began appearing in 1938, most frequently in the *Journal of Aviation Medicine*. Armstrong was solely responsible for developing the physiological specifications that were used to design the 1937 military Lockheed X-35, the first practical pressurized aircraft. The same criteria were applied to the subsequent pressurized, tail-wheeled, Boeing 307 Stratocruiser, introduced on December 31, 1938. Both TWA and Pan Am airlines operated these aircraft on long distance flights. These were the first airline aircraft to have an engineer's position, due to the need to monitor and control the pressurization system.

With respect to the new Boothby, Lovelace, and Bulbulian oxygen mask, Armstrong, upon receiving a copy for testing, suggested improvements that included covering the mouth and adding a microphone. In addition, breath moisture tended to freeze shut the metal valves, and Armstrong suggested a fix for this. Adoption of these suggestions led to a very successful mask that the Mayo Clinic patented, with the Air Corps paying royalties as the mask came into wide Air Corps use.

Armstrong continued to undertake altitude chamber studies, periodically as a subject. He found that an open container of blood would "boil" at 19,530 m (63,000 ft), an altitude that became known as *Armstrong's Line*. In 1939, he authored the textbook, *Principles and Practice of Aviation Medicine,* a book that proceeded through three updated editions (11).

Armstrong with Drs. Boothby and Lovelace received the Collier Trophy in 1940 for their mask development and contributions to aviation safety. In 1949, Armstrong was named Surgeon General of the U.S. Air Force. In this same year, he established the Department of Space Medicine, USAF SAM, Randolph Field, Texas.

He retired from the Air Force as a Major General in 1957. In 1982, he received the Edward P. Warner Award of the International Civil Aviation Organization for his singular contributions for pressurized flight. The only other American to have received this award was Charles A. Lindbergh.

Armstrong passed away on February 5, 1983, just shy of his 84th birthday. On July 18, 1999, Armstrong was enshrined in the National Aviation Hall of Fame, the second physician to have been so recognized (the first was John Paul Stapp). He left a legacy of peace and wartime contributions in aerospace medicine, including 105 scientific publications, a life that materially contributed to progress in aviation advances and space flight development.

CIVIL AVIATION MEDICINE

Louis Hopewell Bauer, born on July 18, 1888, Boston, Massachusetts, saw his first airplane flight as a youth in Boston. His lifelong devotion to aviation began on that occasion (12). With a bachelor of arts degree from Harvard (1909) and a doctor of medicine degree from Harvard (1912), Bauer accepted a commission as a first lieutenant in the Army Medical Corps, and attended the Army Medical School from 1913 to 1914. He served on the Mexican border, in the Philippines, and at Kelly Field, San Antonio. In this latter assignment, he served with the first aviation unit and was promoted to the temporary grade of Lieutenant Colonel. He succeeded Col. William H. Wilmer as the Director of the Medical Research Laboratory and led its post–World War I move from Hazelhurst Field to nearby Mitchel Field, Long Island. In March 1921, the laboratory burned down and Bauer oversaw its reconstruction. He established a school for flight surgeons that was designated on November 8, 1922, as the School of Aviation Medicine. In 1922, the Navy began to send medical officers to the school to qualify as flight surgeons. The Navy subsequently established its own flight surgeon school on November 20, 1939, designated as the School of Aviation Medicine, Pensacola, Florida.

In August 1925, following 6 years as commandant of the Army School of Aviation Medicine, Dr. Bauer was enrolled in the Army War College, Washington Barracks (the Barracks subsequently became Fort McNair). During this time, he finalized a textbook, *Aviation Medicine*, published with the authority of the Surgeon General in January 1926 (10). In the summer of 1926, he completed the Army War College and was assigned to Fort Benning, Georgia.

On May 20, 1926, President Calvin Coolidge signed the Air Commerce Act. Secretary of Commerce, Herbert Hoover, obtained Bauer's release from the Army Air Service, and Bauer accepted the position of Director of the Medical Service in the Aeronautics Branch of the Department of Commerce, effective November 16, 1926. He immediately set to work and prepared the first federal civilian medical standards for pilots, Section 66, "Pilots' physical qualifications," contained in pages 31 to 32 of the 45-page *Air Commerce Regulations*, published and effective December 31, 1926, Government Printing Office, Washington, D.C.

The physical standards read: "Private Pilots. Absence of organic disease or defect which would interfere with safe handling of an airplane under the conditions of private flying; visual acuity of at least 20/40 in each eye; (<20/40 may be accepted if the pilot wears a correction in his goggles and has normal judgement of distance without correction), good judgement of distance, no diplopia in any position; normal visual fields and color vision; no organic disease of the eye or internal ear."

"Industrial Pilots. Absence of any organic disease or defect which would interfere with the safe handling of an airplane; visual acuity of not less than 20/30 in each eye, although in certain instances less than 20/30 may be accepted if the applicant wears a correction to 20/20 in his goggles and has good judgement of distance without correction; good judgement of distance; no diplopia in any field; normal visual fields and color vision; absence of organic disease of the eye, ear, nose or throat."

"Transport Pilots. Good past history; sound pulmonary, cardiovascular, gastro-intestinal, central nervous and genito-urinary systems; freedom from material structural defects or limitations; freedom from disease of the ductless glands; normal central, peripheral and color vision, normal judgement of distance; only slight defects of ocular muscle balance; freedom from ocular disease; absence of obstruction or diseased conditions of the ear, nose, and throat, and no abnormalities of the equilibrium that would interfere with flying."

Waiving the physical standards to permit certification was provided for in the regulations. The policy provided: "In the case of trained, experienced flyers, the Secretary of Commerce may grant waivers for physical defects designated as disqualifying by these regulations, when in his opinion, the experience of the pilot will compensate for the defect. A waiver once granted will hold indefinitely so long as the defect for which it was granted has not increased or unless cancelled by the Secretary of Commerce."

In March 1927, the classification of pilots was broadened to four classes, and the status of student pilots was clarified, "Limited Commercial" was added to the other classes named, and student pilots were included as part of the private pilot class.

Standards for transport and limited commercial pilots were the same, with physical examination and medical certificate renewal required every 6 months. Standards for industrial and private pilots (including student pilots) were also identical. Physical examination and medical certificate renewal for these two classes was required every 12 months. With the exception of the less stringent visual requirements for industrial and private pilots, the new civilian physical standards were essentially the same as those then in use for pilots of the Army Air Corps. Dr. Bauer, backed by his Army experiences, together with the opinions of his aviation medicine contemporaries, meant to hold a tight rein on granting waivers (13).

Bauer's certification system for civilian pilots utilized "aviation medical examiners (AMEs)." The first 57 AMEs who were selected were announced on February 28, 1927. By June 30, 1927, Bauer had appointed 125 AMEs. In addition, army and navy flight surgeons were also qualified to make the examinations. In addition, examination fees were set.

Dr. Bauer proposed district (regional) flight surgeons in 1928. He hired Harold J. Cooper, MD as assistant medical director on April 20, 1929. He initiated and conducted 12 training conferences for AMEs during the period 1929 to 1930. Dr. Cooper studied the relationship between physical deficiencies and pilot training success. He also correlated pilot physical deficiency data with aircraft accidents. Although not a coauthor, it is thought that Bauer had encouraged and participated in Dr. Cooper's studies. Dr. Cooper found that there were 50% more aircraft accidents, both total and fatal, among pilots who had physical defects during the 1927 to 1929 period. He also found a three times attrition for pilots with defects during the period.

On December 15, 1928, Dr. Bauer met with 29 AMEs in his office. The group decided to form the "Aerial Medical Association," with Bauer as temporary chairman. The group formed a tentative constitution and bylaws a few weeks later, and changed the name to *Aero Medical Association of the United States*. The first annual meeting was held on October 7 and 8 in Detroit, Michigan. The venue was the Statler Hotel and Dr. Bauer was elected President. Dr. Bauer was reelected President for the period 1930 to 1931, and became a driving force in launching the Association's new journal, *The Journal of Aviation Medicine*. Volume I, No. 1, March 11, 1930. The editor in chief was Robert A. Strong, MD, Tulane University Medical School, New Orleans, Louisiana. The first journal issue was 62 pages in length, with the 20-page lead paper by Dr. Cooper, reporting his studies as cited in the preceding text. Another of the several papers was that by Dr. Longacre titled *Personality Study*.

Dr. Bauer resigned his position on November 26, 1930, possibly due to the medical branch being buried deeper within the Department of Commerce. There were some industry complaints that the medical standards were too stringent, hampering the hiring of pilots, and some thought that responding to these was an irritant to Bauer. Dr. Bauer had a strong desire to enter the private clinical practice of cardiology, and he established a practice in Hempsted, Long Island, adjacent to Mitchel Field. He became Secretary-General of the World Medical Association in 1948, and he became president of the American Medical Association (1952–1953).

It is noted that Dr. Bauer was influential in the establishment of maximum daily and monthly flying times for pilots (settling on 8 hours/day, 85 hours/month). He fostered the creation of airline medical departments. He promoted international participation with respect to the activities of the Aero Medical Association. He worked to increase the number of military flight surgeons on flying status. The Department of Commerce paid the AMEs for their examinations but had reduced the payments to $6; Dr. Bauer sought to restore the payments to the higher level.

In a eulogy to William H. Wilmer in June 1936, Bauer held to his personal opinion, previously cited, that the Army hypoxia research was "so thorough and painstaking that overcoming hypoxia was chiefly an engineering problem." Bauer wrote in 1937, "the medical requirements of stratosphere flying are pretty well known." Armstrong demurred, by writing "after 18 years of work we are in the stone age of high-altitude equipment." The March and June 1937 issues of *The Journal of Aviation Medicine* contained 23 abstracts of reports on altitude physiology, 22 of them from Germany.

Drs. Armstrong and Bauer are shown together at the 1958 meeting of the Aero Medical Association (Figure 1-7). Dr. Bauer received numerous awards during his career lifetime, including the first Theodore C. Lyster award in 1947. He had helped establish board certification in aviation medicine, February 1953, under the American Board of Preventive Medicine. He received aviation medicine specialty diploma Number One. In June 1963, the name of the specialty was broadened to the current *aerospace medicine*.

There were numerous critics of the medical standards and the designated examiner system. One critic was the first

FIGURE 1-7 Drs. Harry G. Armstrong (*left*) and Louis H. Bauer, two outstanding pioneers and leaders in aerospace medicine, at the 1958 meeting of the Aero Medical Association.

Assistant Secretary of the Navy for Aeronautics, Edward P. Warner (the namesake for the award bestowed by the International Civil Aviation Organization on Dr. Armstrong in 1982 as cited earlier). Warner became editor of *Aviation* magazine in 1929. He noted that there were articles stating that pilots needed eagle eyes and extra powers to gaze into space. He said that the supply of eagle eyes was limited and that the accidents in newer aircraft were due to pilot folly and lack of temperamental balance. He felt that research in determining ability to fly should be shifted from physiologic measures in medical offices to psychological laboratories in universities. Warner stated that most old-time pilots had an unfavorable anecdote about doctors, so medical directors and AMEs needed to gain the confidence of pilots and congressmen to be effective. He cited an RAF study revealing that pilots with physical defects had fewer accidents than those in perfect health "who were probably reckless." He encouraged further analysis by Drs. Cooper and Bauer of accident/defect correlation data.

Roy E. Whitehead, MD, Medical Director, 1933 to 37, Bureau of Air Commerce, undertook studies of the adequacy of supercharging aircraft cabins for aircrew and passenger oxygen well-being, along with specific studies of aircrew and passenger oxygen requirements. The historical impact of his studies has been largely overlooked.

Armstrong wrote, "Dr. Whitehead has the honor of being the first to present what is most certainly to be the coming method of oxygen administration." Dr. Whitehead conducted studies that found no direct relationship between private flying aircraft accidents and the physical condition of the pilots.

On April 15, 1938, the Bureau of Air Commerce announced the opening of a Medical Science Station in Kansas City, Missouri to investigate aviation medical problems to improve aviation safety. The station, under original AME Wade H. Miller, MD, planned to study pilot fatigue and the effects of "anoxia" on airline transport operations. In addition, studies would be made to create new and more applicable medical standards for commercial and noncommercial airmen. In 1940, owing to controversy over studying pilot fatigue, claims that the station duplicated studies elsewhere, and funding shortages, the station was closed.

Plans were made to open a Houston Medical Center to study pilot medical standards, the detection of heart disease, hypoxia in light aircraft, and aircraft crashworthiness. World War II interrupted implementation of the plans. However, in 1946, the Civil Aeronautics Commission moved its pilot Standardization Center, Ellington Field, Houston, to Will Rogers Airport, Oklahoma City. The proposed medical facility, now named the *Aviation Medical Branch*, was opened along with the Standardization Center at Will Rogers Field. John J. Swearingen was named to head the new medical facility.

In 1953, Swearingen and his small contingent of technical personnel were moved by the Civil Aeronautics Administration (established in 1940 as the civil aircraft and airman Federal regulatory agency, the predecessor to the Federal Aviation Agency of 1958) to Columbus, Ohio, in association with Ohio State University. Medical School personnel were available to work with Swearingen, and he had access to an altitude chamber. The facility was renamed the *Civil Aviation Medical Research Laboratory*. Several reports and research movies began to be produced. One that was frequently referenced concerned explosive decompression effects on a passenger seated near an airline window that suddenly failed at the higher altitudes. The results of this study influenced the design of upcoming aircraft passenger windows. The group also patented for public use a mechanism to deploy passenger oxygen masks in case of decompression. In addition, the first anthropomorphic dummy ("Oscar") was constructed for use in aviation studies such as those failed-window studies mentioned in the preceding text.

In 1958, the new Federal Aviation Agency began enlarging the activities at Will Rogers Field, establishing the Aeronautical Center. The Center grew to include an academy to train agency pilots, air traffic controllers, and other technical personnel, an enhanced airman and aircraft records facility, an updated fleet of aircraft for training and flight checks of air traffic navigation equipment, a Civil Aeromedical Research Institute (into which in March 1960 was folded the Civil Aeromedical Research Laboratory formerly located in Columbus), and other mission support groups.

Swearingen became Chief of the Protection and Survival Branch in the new institute, and conducted new studies on aircrew torso restraint systems and cockpit instrument panel crashworthiness design features. He also studied aircrew and passenger seat designs to absorb crash forces in survivable accidents. The general tolerances of the human face to crash impact forces were determined by Swearingen (Figure 1-8). His associate, Ernest B. McFadden studied the smoke protective hood approach that enabled occupant escape from a burning aircraft should a crash landing occur

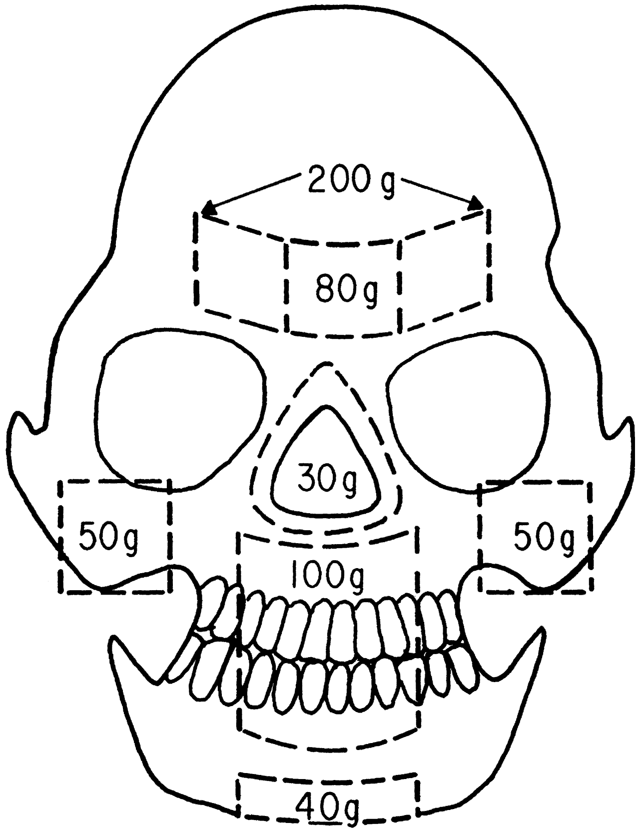


FIGURE 1-8 John J. Swearingen, Protection and Survival Laboratory, Civil Aeromedical Institute, received the Metropolitan Award of Honor for Research in Accident Prevention in 1965 for determination of tolerances of the human face to crash impact.

(Figure 1-9). Also shown in Figure 1-9 is an experimental adhesive oxygen mask for small children, a flotation device for infants should a ditching occur, and an instrumented flotation dummy for studies of various ditching survival equipment.

A Georgetown Clinical Research Institute was established by the Federal Aviation Agency in November 1960 at Georgetown University, Washington, D.C. to study airline pilot aging. The General Accounting Office of Congress discovered in the summer of 1965 that another airline pilot aging study supported by the National Institutes of Health was already under way at the Lovelace Clinic, Albuquerque, New Mexico. In April 1966, the report was sent to Congress that the Georgetown study duplicated the established Lovelace study. The Federal Aviation Agency decided to close the Georgetown facility, and transfer its financial and certain personnel resources on September 30, 1966 to its new Civil Aeromedical Research Institute facility in Oklahoma City, housed in an ultramodern 212,000 sq.ft, four-floor building (three levels above ground).

Studies at the Civil Aeromedical Research Institute between 1960 and 1965 included aerial application pesticide poisoning aspects, in-flight spatial disorientation, alcohol and drug effects on pilot performance, circadian rhythm effects on aircrew, airman vision, airman hearing, sonic boom effects on the public, airman fatigue, cardiac exercise rehabilitation to assist medical certification of pilots, emergency evacuation of airline aircraft, and air traffic controller selection aspects. The evolving advances in faster, larger, and more numerous airline aircraft, steadily moving forward from the 1920s, pressured the Federal Aviation Agency to enhance its airway navigation facilities, its air traffic towers, *en route* air traffic centers, and air traffic controller personnel. In fact, it was the "Grand Canyon" mid-air collision in June 30, 1956, between a United Douglas DC-7 and a TWA Lockheed L-1049 Constellation, killing 53 passengers and 5 crewmembers on the DC-7, and 64 passengers and 6 crewmembers on the Constellation that revealed the serious deficiencies in the Civil Aeronautics air traffic control system. This accident precipitated the government act creating the Federal Aviation Agency in 1958.

WOMEN IN AVIATION

Women have piloted lighter-than-air and heavier-than-air aerial vehicles since 1798, and to the present have piloted all types of civil aircraft, including airline operations, and all types of military aircraft, including combat operations. We must add the Space Shuttle to the mix. Women have regularly set distance and endurance records. Biases slowed training, entry into military aviation, acceptance into commercial aviation activities, and adoption of contributory suggestions they have made. For example, Marie Marvingt, whose air ambulance initiatives have been covered herein earlier, made the first balloon flight across the North Sea in 1909. When the first International Requirements for Commercial Pilots were proposed in 1919, female pilots were to be medically examined every 3 months, and male pilots every 6 months. Pregnancy was disqualifying. Twenty-six countries adopted the standards, but the United States did not. Dr. Bauer is said to have observed that the U.S. standards were not greatly different than the international standards.

On 24 November, 1933, Dr. Roy E. Whitehead succeeded Dr. Raymond F. Longacre as medical director of the Aeronautics Branch, Department of Commerce. Dr. Whitehead proposed a revision of the physical standards for female pilots. He introduced the acquisition of a history on any menstrual abnormalities, pregnancies, and miscarriages. He prepared cautionary information for female pilots to the effect that it is dangerous for them to fly within a period extending from 3 days before menstruation to 3 days after menstruation. He indicated that many women pilots have fainted when flying during this period with fatal results.

Whitehead also indicated that the emotions and the mind are more or less correlated in flying, and that anything that interferes with the normal emotional and mental reactions is bound to disturb the skillful controlling and maneuvering of an aeroplane.

Many physicians did not support Dr. Whitehead's quaint "Victorian" ideas. The female pilot organization, the "Ninety Nines," was also not supportive. Some female pilots did

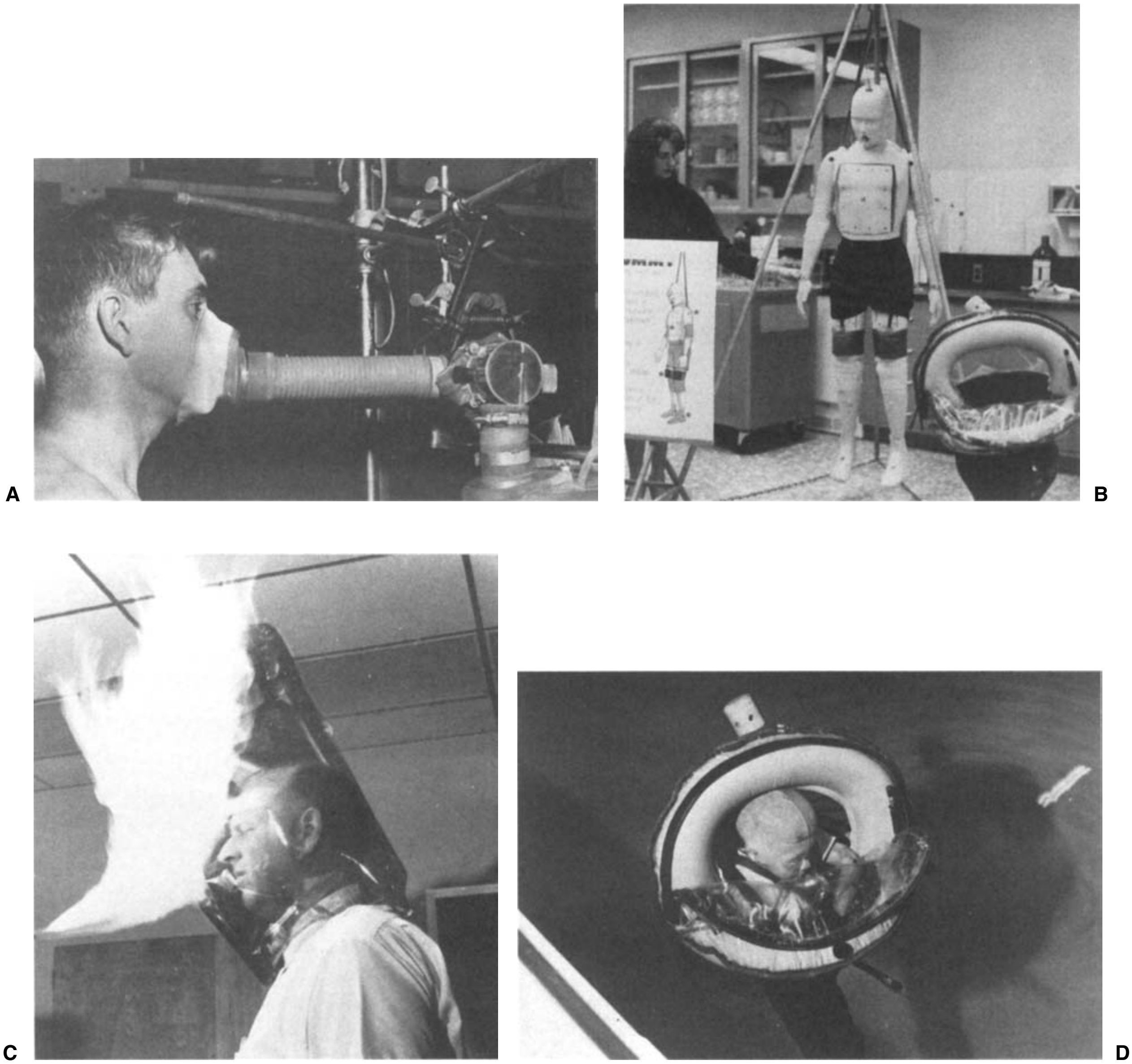


FIGURE 1-9 Federal Aviation Administration's Ernest B. McFadden invented the aneroid-actuated passenger oxygen mask, an adhesive oxygen mask for children, (**A**) the round passenger oxygen mask, (**B**) an instrumented research flotation dummy, (**C**) a smoke protective hood, and (**D**) an infant flotation device.

volunteer that they had experienced nausea and vomiting during pregnancy but were fit to fly 90% of the time. Some of them preferred to discuss these matters with a female physician. In 1933, a complaint by female pilots, including Amelia Earhart, that there were no female AMEs, was partially resolved by the appointment of Clara R. Gross, MD, New York City, Emma M. Kittredge, Los Angeles, and several other female physicians as examiners. Earhart founded the "Ninety Nines" in 1929 with the original group of female pilots numbering 99, with the mission to promote more opportunities in aviation for women. The new Civil Aeronautics Authority established on June 23, 1938, led to subsidized training costs for 10,000 pilots; but only 10% could be women.

Jacqueline Cochran (1906–1980) was accomplishing numerous aviation firsts for women during the 1930s. In 1937, she made the first blind landing by a female pilot. She repeatedly entered major air races, winning the Transcontinental Bendix Trophy race on September 23, 1938, flying a new all-metal Seversky P-35 fighter aircraft. She was awarded the Harmon International Trophy in 1940. On September 11, 1942, at the request of General Henry "Hap" Arnold, she became director of Women's Flying Training, Avenger Field, Sweetwater, Texas. This activity became the Women's Air force Service Pilots (WASPs) on August 5, 1943. The pilots delivered aircraft domestically and internationally as needed, including fighters and bombers. Some even flew B-29s. On December 20, 1944, the WASP program was deactivated. Ms. Cochran, however, continued her career. On May 18, 1953 she flew an F-86 Canadair Royal Canadian Air Force Sabre jet following consultation with Chuck Yeager through Mach 1 at 1,007 kph (625.5 mph), and on June 3, 1964 she flew an F-104G Starfighter through Mach 2 at 2,300 kph (1,429 mph). During her flying career that extended from 1932 for 33 years, she held more major speed and altitude records than any other pilot, numbering more than 200.

Lauretta M. Schimmeler in 1932 recognized the need for specially educated registered nurses to be available for air ambulance and other aviation assignments. The need was implemented in 1942 when the Army Nurse Corps urgently appealed for graduate nurses with flight attendant experience to accompany medical evacuation flights. The first class had 39 graduates. More than 1,000,000 patients were evacuated by military air transport from 1944 to 1945, and officials concluded that the use of nurses was a wise move.

Dr. Jeannette Ridlon Piccard, who piloted a balloon to a flight altitude record of 17,550 m (57,579 ft), used a pressurized gondola, on October 23, 1934. Accompanying her was her husband, Dr. Jean Piccard, twin brother of Auguste, mentioned in the subsequent text. The National Geographic Society, the traditional backer of such flights, refused to support her flight, stating that they would have nothing to do with sending a woman and mother in a balloon into danger. The flight originated in Dearborn, Michigan, and landed in Cadiz, Ohio.

Jeannette Piccard was the first woman to enter the stratosphere. The unsung heroines in aviation are the tens of thousands of women airline flight attendants (although many men are now flight attendants as well). They are no longer nurses as originally introduced in 1929. Safety and comfort of airline passengers continue to be their primary role. With respect to in-flight passenger illness, the occasional in-flight decompressions, and the rare emergency evacuations, the flight attendant is the first line of assistance. The availability of medical emergency kits and automatic defibrillators provide flight attendants with tools for aid in case of in-flight medical emergencies. In many cases, a call for a physician-passenger or other health professional who may be on board, provides professional assistance.

ON THE THRESHOLD OF SPACE

In 1935, the Department of Commerce formed a Government Stratosphere Committee that included Amelia Earhart and Igor Sikorsky. A special related committee for aviation medicine was formed that included Drs. Armstrong, Bauer, Whitehead, Grow, Tuttle, Dill and McFarland. Captain Hawthorne Gray's fatal flight to 12,192 m (40,000 ft) using an open wicker basket, on November 4, 1927, had emphasized the need for a pressurized aircrew environment.

On December 7, 1934 over Bartlesville, Oklahoma, Wiley Post using his Lockheed Vega, *Winnie Mae*, and equipped with a pressure suit of his and the B.F. Goodrich Company design, reached the unofficial altitude of 15,240 m (50,000 ft). He was assisted in developing the suit by 1934 altitude chamber tests at Wright Field. He used an Army Air Corps liquid oxygen system to keep the suit inflated. During the December 7, 1934 flight, he encountered 322 kph (200 mph) west to east winds (he had entered the jet stream, the first person to do so). On March 5, 1935, Post flew from Burbank, California, at stratospheric cruising altitudes, nonstop to Cleveland, Ohio. He had flown 3,275 km (2,035 mi) in 7 hours and 19 minutes, averaging a ground speed of 449 kph (279 mph), which was approximately 161 kph (100 mph) faster than the Vega's maximum normal cruising speed. At times, the flight had a ground speed of 547 kph (340 mph); Post was riding the jet stream. By June 15, 1935, Post's several pressure-suit assisted high-altitude flights had provided him with more time at speeds exceeding 483 kph (300 mph), and more time piloting an aircraft in the stratosphere than any other person. The aviation community recognized his demonstration of the coming era of pressurized commercial and military flight.

Any discussion of Wiley Post must include some of his personal history along with his aeronautical achievements. He was born on November 22, 1898, Grand Saline, Texas. He saw his first airplane at the Lawton County Fair during 1913, a Curtiss Pusher flown by demonstration pilot Art Smith. The aerobatics excited him and he vowed to become a pilot. He managed to attend in 1916 the Sweeney Auto School in Kansas City (providing him with reciprocating engine knowledge). When the United States entered World War I in April 1917, he enrolled in the Students Army Training Corps, Norman, Oklahoma, and was sent to Section B of the Radio School. With the end of the War, Wiley joined a barnstorming group, the "Texas Topnotch Flyers," as a parachutist and caught a few minutes of flight training from time to time in the Curtiss JN-4 "Jennies." He made 99 parachute jumps and decided to work with an oil-drilling crew to make enough money to purchase his own airplane to sell rides. On October 1, 1926, while on a drilling rig near Seminole, a chip of metal from a roughneck's sledgehammer flew into his left eye. It had to be enucleated. Post was awarded $1,800 compensation by the Oklahoma State Industrial Court. Despite having only one eye, Post had no trouble with flying and was known for his abilities, and the new medical standards of Dr. Bauer had not yet reached Oklahoma. When they did, Post received a waiver. Two Oklahoma oilmen, F.C. Hall and Powell Briscoe, hired Post to fly them to various parts of Oklahoma and Texas to beat their competitors to sites where oil leases could be accomplished (using a 1928 Travel Air Model 4000). On March 27, 1930, Hall ordered a new Lockheed 5B Vega, license No. NC105W. Post, who had received his air transport license, took delivery. On August 27, 1930, Post won the Los Angeles to Chicago Air Derby with this airplane, beating more experienced, senior, and nationally famous pilots such as Art Goebel, Roscoe Turner, Billy Brock, and Leland Schoenhair. Again, monocular vision did not appear to be a handicap.

F.C. Hall, as noted in the preceding text, named the airplane after his daughter, *Winnie Mae*. Hall paid for Post and Harold Gatty (navigator) to make the first rapid circumnavigation of the globe. The flight started at Roosevelt Field, New York, and the route included Newfoundland, Europe, Russia, Alaska, Canada, and east across the upper United States to Roosevelt Field. The elapsed time was 8 days, 15 hours, and 51 minutes. The June 23 to July 31, 1931 flight set numerous records and brought acclaim and medals to the pilot and navigator. From the aviation medicine standpoint, Post was one of 3259 certified transport pilots at the time.

Post published that he fought fatigue during the 8 days of hard flying at all hours by taking catnaps when away from the plane on brief layovers and by eating lightly. His parts of the postflight book with Gatty contain the statement: "I knew that the variance in time as we progressed would bring on acute fatigue if I were used to regular hours." Post was the first in aviation to publish on the diurnal topic that became known after World War II as *circadian rhythm disruption in long distance flying*. He noted "So, for the greater part of the winter before the flight, I never slept during the same hours on any two days in the same week." One can argue whether or not this was a good training program, but Post felt that it served him well to understand his alertness reactions to irregular hours.

F.C. Hall sold the airplane to Post, who immediately decided to fly solo around the same route. Oklahoma businessmen and major aeronautical industries contributed money and equipment. To aid in offsetting the pilot workload, a Sperry autopilot was provided. Post would make the first long-distance flights with the apparatus. The U.S. Army Signal Corps installed a new radio direction finder (some parts still classified) to aid navigation by tuning to standard broadcast stations along the route. To aid short field take-offs, the airplane was equipped with a newly developed Smith controllable pitch propeller.

Again, as in 1931, Post practiced breaking regular sleeping habits and eating lightly, one meal a day. Post departed solo from Floyd Bennett Field, New York, at 5:10 AM, on July 15, 1933, and flew nonstop to Berlin, Germany. He continued around the globe along the 1931 flight path, but with fewer landings (12 instead of 15). He landed back at Floyd Bennett at 11:59 PM and 30 seconds, on July 22, 1933. The trip took 7 days, 18 hours, and 49.5 minutes. A crowd of 50,000 greeted Post on arrival, and he was given his second New York City ticker tape parade (his first was after the 1931 world flight).

Further with respect to balloon flights, Swiss physicist Auguste Piccard using a sealed gondola and an oxygen supply plus an apparatus (scrubber) to remove carbon dioxide, ascended with Paul Kipfer on May 27, 1931, to 15,606 m (51,200 ft). For impact protection on take-off and landing, each balloonist wore wicker chicken baskets containing pillows around his head. Scientific atmospheric measurements were made during the flight.

Navy Lieutenant Commander Thomas Settle and Marine Corps Major Chester Fordney made balloon flights related to the 1934 Chicago World's Fair. During these flights they searched for an ozone layer with an infrared camera and carried an apparatus to measure cosmic rays for Arthur Compton and Robert Millikan.

During the mid-1930s, balloonists in Europe, including the Soviet Union, experimented with high-altitude flights. In the United States, Armstrong served as advisor to Captains Albert W. Stevens and Orvil A. Anderson who ascended in the gondola of Explorer II to 22,066 m (72,395 ft) on November 11, 1935. Liquid air instead of liquid oxygen was used because of the latter substance's fire hazard potential. The balloonists' equipment found that the ozone at the higher altitudes blocked most of the ultraviolet rays of the sun. It was also shown that the percentage of oxygen in the atmosphere at 21,336 m (70,000 ft) was essentially the same as that at sea level.

On June 24, 1943, Col. W. Randolph Lovelace, MD jumped from a B-17 at an altitude of 12,253 m (40,200 ft), and flying at 322 kph (200 mph), to demonstrate the viability of using oxygen from an attached bailout bottle (12 minutes of oxygen) should an emergency escape be necessary. He opened his chute early in the thin -10°C (minus 50°F) high-altitude atmosphere experiencing an opening shock deceleration of approximately 32 Gs (see Chapter 4). This shock was much greater than at lower altitudes, and resulted in the loss of Lovelace's left glove that caused severe frostbite to his hand. The opening shock caused a loss of consciousness that was regained at lower altitudes. The oxygen bailout bottle worked, and Dr. Lovelace landed approximately 24 minutes after jumping.

Aircrew members were advised following Dr. Lovelace's findings to delay opening their chutes when jumping at high altitudes until reaching a suitable lower altitude providing higher air density and reduced terminal velocity.

Major David G. Simons piloted a balloon starting 09:22 AM on August 19, 1957 from Crosby, Minnesota, in a sealed aluminum capsule, reaching the altitude of 30,942 m (101,516 ft). For this flight, named *Man-High*, Simons wore a pressure suit. He was the first person to spend the night in the stratosphere. He landed the next day at 5:30 PM, Elm Lake, South Dakota. He observed the stars without atmospheric scintillations, and reported that at times he felt an illusion of being detached from earth subsequently termed *the breakoff phenomenon*. Perhaps due to his description of this illusory sensation, future travelers at extreme heights were prepared to understand and disregard the reported subjective feeling should it appear. A contributing factor may have been a sleep deficit, because Simons was sealed in the capsule at 11:00 PM the night before lift-off. The project proved the effectiveness of the onboard life support equipment. On 16 August 1960, Colonel Joe Kittinger parachuted from 31,330 m (102,800 ft) altitude, reaching a terminal velocity in the higher altitudes of 990 kph (614 mph). This pioneering experiment proved that astronauts operating anticipated future spacecraft could successfully escape at high altitudes.

With respect to restraint system protection of occupants in high-performance aircraft, Colonel John Paul Stapp made high-speed rocket-powered sled studies with himself as subject. On December 10, 1954, in a forward facing seat and wearing a flight suit and helmet, Stapp reached 1,027 kph (638 mph), with a sudden deceleration during 1.4 seconds of 35 Gs. This demonstration of human tolerance to extreme crash forces, through use of upgraded restraint systems, resulted in modifications across the spectrum of military and civilian aircraft (and road vehicles).

On October 14, 1947, Charles "Chuck" Yeager (1923–) piloted the instrumented Bell X-1 rocket plane dropped from a Boeing B-29 past Mach 1.0 to Mach 1.06, becoming the first human credited with exceeding the speed of sound. The record flight was made over Muroc Army Airfield (now Edwards Air Force Base) California, at an altitude of 13,106 m (43,000 ft).

On November 20, 1953, Albert Scott Crossfield (1921–2006) piloted the Douglas D-558-2 (no. 2) Skyrocket following its drop from a Boeing B-29 to Mach 2.005, becoming the first human to travel in excess of twice the speed of sound. The altitude of the flight reached 18,897 m (62,000 ft) with the landing at Edwards Air Force Base (name change made on December 8, 1949 in place of Muroc Army Airfield).

On October 4, 1957 the Russians launched Sputnik 1, the first successful artificial earth satellite. On November 3, 1957, they launched Sputnik 2, carrying the dog Laika. The cabin had monitors for ground receivers, including a television camera, plus cabin ambient pressure and temperature sensors. On May 28, 1959, the United States launched "Able," a rhesus monkey, and "Baker," a squirrel monkey, atop a Jupiter AM-18 rocket. These were the first living beings successfully launched and recovered from space. Sputnik 5 was launched on August 10, 1960, with two dogs, Belka and Strelka, two rats, 40 mice, and some plant types. The spacecraft was recovered the next day, all on board surviving.

From June 8, 1959 to October 24, 1968, 13 test pilots variously flew three North American X-15 rocket aircraft in a program involving 199 flights, each dropped from a Boeing B-52 bomber. The pilots progressively expanded the flight envelope, reaching on Flight 188 a speed of Mach 6.70 at 7,274 kph (4,420 mph), and on Flight 91 a suborbital altitude of 107,960 m (354,200 ft). At the "space equivalent" altitudes, aerodynamic control surfaces are ineffective, requiring reaction jets for controlling roll, pitch and yaw. Two of the X-15 test pilots, Neil Armstrong and Joe Engle, became NASA astronauts.

ASTRONAUTS ARRIVE

April 12, 1961 saw Russian military pilot, Yuri Alexeyevich Gagarin, launched into space from the Baikonur site on Vostok 1. His 1-hour 48-minute earth-orbiting flight at an altitude of 303 km (188 mi) informed the world that a new era of human travel had begun. He landed by parachute descent in Kazakhstan. The Russians elected to use the term *cosmonaut* (solar system sailor) vice *astronaut* (sailor among the stars).

The United States selected the Goodrich Company to make improvements in Wiley Post's soft pressure suit that enabled walking in preparation for the planned Project Mercury space flights. On May 5, 1961, Alan B. Shepard was launched from Cape Canaveral, Florida, on a Mercury MR-3 (Redstone rocket), for a 17-minute 26-second downrange suborbital flight. Shepard, the first American astronaut to fly in NASA's program utilizing rocket powered launches, reached an altitude of 188 km (117 mi), flying 486 km (302 mi), for a parachute descent to a water landing. The pressure suit was worn as a backup in case of a cabin pressure problem.

The Russians sent Gherman Stepanovich Titov in Vostok 2 on August 6, 1961 on a 25-hour 18-minute flight, from which Titov gave the first report of a space medicine phenomenon, "space motion sickness." On February 20, 1962, John Hershel Glenn made the first U.S. orbital space flights in a Mercury MA-6 (Atlas rocket), lasting 4 hours 55 minutes (three orbits). On a night flyover of Australia, people across Perth turned their lights on, and, as a study on visual acuity from space, Glenn accurately reported the event. In-flight blood pressure readings, electrocardiogram tracings, and body temperature data were sent by telemetry to NASA ground receiving stations.

The astronaut missions to the lunar surface, reached initially by Apollo 11 that departed Cape Kennedy on July 11, 1969, must be highlighted. Astronauts Neil A. Armstrong and Edwin E. "Buzz" Aldrin, Jr., stepped onto the lunar surface on July 20 while Michael Collins orbited overhead in the Command and Service Module. Armstrong and Aldrin conducted 2.5 hours of surface extra vehicular activity, collecting 22 kg (48 lbs) of lunar surface material, setting up experiments, and taking photographs followed by lift-off. They splashed down in the Pacific on July 24, 1969.

In the Apollo series, a total of 12 individuals in six flights of two each, walked on various areas of the lunar surface, collecting samples, driving a lunar roving vehicle, and conducting experiments. The roving vehicles were used on Apollo missions 15, 16, and 17. On Apollo 17, the vehicle was driven more than 100 km around the lunar surface. During each flight, the Command and Service Module colleague assisted from lunar orbit, adding an additional six individuals who orbited the moon. Apollo 17 launched on December 7, 1972 and returned to earth on December 19, the last of the Apollo flights. The role of aerospace medicine throughout the above explorations is a foundational component with respect to the past, present, and future successes of space missions.

May the future hold great advances in all aspects of aerospace medicine, including more international cooperation, and participation in space by many more nations. In drawing this succinct chapter to a close, it should be noted that future editions may cover the multiple Russian, U.S. and Chinese orbital missions, the shuttle missions, and the space stations (Skylab series, Russian Mir, and the International Space Station).

REFERENCES

1. Bert P. *Barometric pressure*. Translated by MA Hitchchock and FA Hitchcock. Columbus, Ohio: College Book Company, 1943.
2. Jeffries J. A narrative of the two aerial voyages of Doctor Jeffries with Mons. Blanchard. *Aviat Space Environ Med* 1984;55:993–999.
3. Jeffries J. A narrative of the two aerial voyages of Doctor Jeffries with Mons. Blanchard. *Aviat Space Environ Med* 1985;56:99–104.
4. Armstrong HG. *Principles and practice of aviation medicine*, 3rd ed. Baltimore: Williams & Wilkins, 1952.
5. Lam DM. To pop a balloon: aeromedical evacuation in the 1870 siege of Paris. *Aviat Space Environ Med* 1988;59:988–991.
6. War Department, Air Service, Division of Military Aeronautics. *Air service medical*. Washington, DC: US Government Printing Office, 1919.
7. Hildebrand JR. Man's amazing progress in conquering the air. *Natl Geogr Mag* 1924;46:112.
8. Wells HV. The flying service from a medical point of view. *J R Nav Med Serv* 1915;1:55–60.
9. Armstrong HG, ed. *Aerospace Med*. Baltimore: Williams & Wilkins, 1961.
10. Bauer LH. *Aviation medicine*. Baltimore: Williams & Wilkins, 1926.
11. Armstrong HG. *Principles and practice of aviation medicine*. Baltimore: Williams & Wilkins, 1939.
12. Benford RJ. *Doctors in the sky*. Springfield: Charles C Thomas Publisher, 1955.
13. Holbrook HA. *Civil aviation medicine in the bureaucracy*. Bethesda: Banner Publishing Company, 1974.

RECOMMENDED READINGS

Collins WE, Wade K. *A milestone of aeromedical research contributions in civil aviation safety: the 1000th report in the CARI/OAM series*. Washington, DC: Office of Aerospace Medicine, 2005; DOT/FAA/AM-05/3 3.

Engle E, Lott A. *Man in flight: biomedical achievements in space*. Annapolis: Leeward Publications, 1979.

Fisher AC, Marden L, Jr. *Aviation medicine on the threshold of space*. *Natl Geogr Mag* 1955;58(2):241–278.

Hansen JR. *First man, the life of Neil A. Armstrong*. New York: Simon & Schuster, 2005.

McFarland RA. *Human factors in air transportation*. New York: McGraw-Hill, 1953.

Mohler S, Johnson B. *Wiley post, his winnie mae, and the world's first pressure suit*. *Smithsonian annals of flight*, No. 8, Washington, DC: Smithsonian Institution Press, 1971.

Post W, Gatty H. *Around the world in eight days*. Garden City: Garden City Publishing Company, 1931.

Robinson DH. *The dangerous sky*. Seattle: University of Washington Press, 1973.

Ryan C. *The pre-astronauts*. Annapolis: Naval Institute Press, 1995.

CHAPTER 2

Respiratory Physiology and Protection Against Hypoxia

Jeb S. Pickard and David P. Gradwell

> There is something fascinating about science. One gets such a wholesale return of conjecture from such a trifling investment of fact.
>
> —*Mark Twain, Life on the Mississippi*

RESPIRATORY PHYSIOLOGY

Respiration is the process by which an organism exchanges gases with the environment and, for most aerobic organisms, the critical portion of respiration consists of ensuring an adequate supply of oxygen. There is considerable geologic evidence that the Earth's original atmosphere was anoxic, and it seems probable that life began under anaerobic conditions. Because habitable environments available to anaerobic organisms became relatively scarce due to the shift toward an oxidizing atmosphere, the development of enzyme systems capable of both utilizing and detoxifying oxygen was a practical necessity. This evolutionary step had an added ramification because the utilization of a reactive element such as oxygen unleashed a source of energy that allowed the development of ever more complex multicellular organisms. In turn, this required a more or less elaborate system capable of effective oxygen delivery.

The process of respiration is a simple one for unicellular organisms with gases exchanged through passive diffusion. Even in the most complex multicellular organisms, individual cells continue to passively exchange gases with their local environment in a similar manner. In complex organisms, however, each cell is surrounded by other cells competing for the same oxygen and eliminating carbon dioxide, which leads to several requirements. One requirement is an adequate source of oxygen, the definition of "adequate" depending in part on the metabolic rate, and another is an efficient delivery system. The poor solubility of oxygen in water impacts both requirements. For mammals, the source must be gaseous, with a sufficient pressure of oxygen. Gills are adequate to support poikilothermic organisms but, even in a tumbling mountain stream, the oxygen content of water is trivial compared to air. Also, for all but the simplest of multicellular organisms, the solubility of oxygen requires that the delivery system includes a carrier molecule.

In humans, the limbs of the oxygen delivery system consist of the following:

- Ventilation—the process whereby pulmonary alveoli exchange gas with the atmosphere. Problems that may impact this part of the system include inadequate atmosphere, such as a hypoxic or hypercarbic environment, and airway obstruction.
- Pulmonary diffusion—the process whereby gases are exchanged between the alveolus and the pulmonary capillary. The process of diffusion itself is simple and efficient, and clinical problems are rare. Most pulmonary problems that result in systemic hypoxia represent a failure to topographically match ventilation with perfusion.
- Transportation—the shuttling of gases between lung and tissue, and back, through the vascular system. Clinical diseases related to oxygen transportation are common, and include anemia, hemorrhage, deficient cardiac output, and obstruction to blood flow.
- Tissue diffusion—the exchange of gases between systemic capillaries and tissue cells. Again this is a simple process, although it can be impeded by increasing the distance between capillary and target cell, such as by tissueb edema.
- Cellular utilization—the chemical reactions occurring within cells that employ oxygen. Compounds that interfere with these processes, such as cyanide, are toxic to most aerobic organisms.

Ventilation

Functional Anatomy of the Airways

In the normal human at rest, air is essentially completely humidified and warmed by the time it reaches the end of the trachea. From mainstem bronchi to the terminal bronchioles, the function of the airways is to conduct air to the respiratory zone. Because the airways from the nares to the terminal bronchioles do not participate in gas exchange, they constitute the anatomic dead space. In a normal adult male, this averages 150 mL at rest, although functional dead space may be increased by the addition of a rebreathing chamber, such as a mask. The resting bronchial tone found in normal airways serves to reduce anatomic dead space and thereby wasted ventilation, the trade-off being increased resistance to flow. Inflammation of the airways from a variety of causes commonly results in increased bronchial tone resulting in asthma, one of the most common diseases to afflict mankind.

Upon leaving the terminal bronchioles, gas flow enters the respiratory zone, comprising the respiratory bronchioles, alveolar ducts, and alveolar sacs. Although the total cross-sectional area of the airways increases as air flows peripherally, this increase is particularly dramatic as gas reaches the respiratory zone, and results in marked slowing of airflow velocity. Indeed, at this point the primary means of gas transport begins to be diffusion rather than convection, and gas movement is completely governed by diffusion at the level of the alveoli.

With levels of ventilation exceeding 8,000 L of air over a 24-hour period, the respiratory system is second only to the integument in exposure to the environment, and is necessarily far more delicate. Despite this constant assault, the parenchyma and distal airways are kept in a state of functional sterility by the mucociliary clearance system. The ciliated and secretory epithelial cells comprising this system constitute most of the cellls lining the conducting airways. Thin mucoid secretions float atop a watery sol layer, capturing particulate matter, and are wafted up the tracheobronchial tree to be passed through the glottis and swallowed. Although these secretions average approximately 100 mL/d, the normal individual is usually unaware of their production, a situation that changes when noxious stimuli such as infection, inflammation, or oxygen toxicity result in both impaired ciliary function and thickened secretions.

Lung Volumes

With each breath, the average adult at rest moves approximately 400 to 500 mL of air, an amount known as the *tidal volume* (TV). Inhalation is active, predominantly with the diaphragm, whereas exhalation is usually passive. The volume of air remaining in the lungs at the end of a passive exhalation is known as the *functional residual capacity* (FRC), and is determined purely by the balance between the elastic properties of the lung and the chest wall. If one exhales completely, the amount of air exhaled is designated as the expiratory reserve volume (ERV), and the remaining air that cannot be expelled (in the absence of a blow to the epigastrium) is known as the *residual volume* (RV). If instead one makes a maximal inspiratory effort from FRC, the volume inhaled is designated as the inspiratory capacity (IC), and the total volume of gas contained in the lungs is known as *total lung capacity* (TLC). The difference between TV and IC is designated the inspiratory reserve volume (IRV). The maximal amount of air that can be expelled from full chest expansion is the vital capacity (VC). These volumes and capacities are illustrated in Figure 2-1.

Average normal values for young adults are given in Table 2-1.

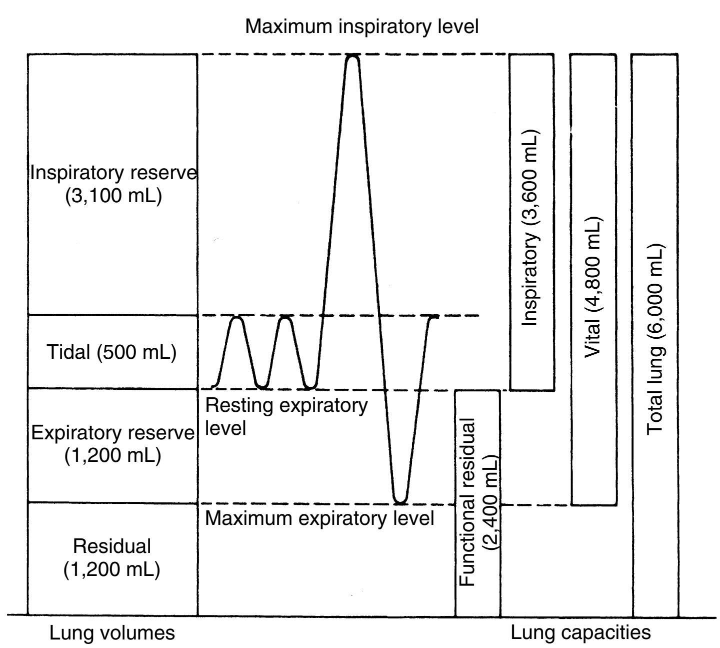


FIGURE 2-1 Lung measurements.

TABLE 2-1

Lung Volumes in Healthy Subjects 20 to 30 Years of Age

Functional Measurements	*Approximate Values (mL)* *Males*	*Females*
Tidal volume (TV)	500	450
Inspiratory reserve volume (IRV)	3,100	1,950
Expiratory reserve volume (ERV)	1,200	800
Residual volume (RV)	1,200	1,000
Inspiratory capacity (IC)	3,600	2,400
Functional residual capacity (FRC)	2,400	1,800
Vital capacity (VC)	4,800	3,200
Total lung capacity (TLC)	6,000	4,200

(Modified from Comroe JH Jr. *Physiology of respiration*. Chicago: Yearbook Medical Publishers, 1965.)

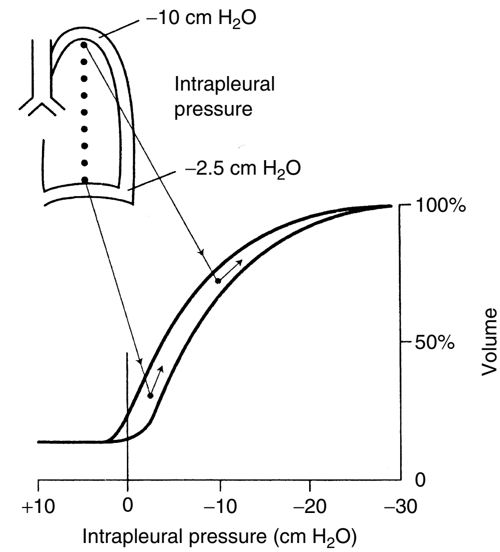


FIGURE 2-2 Explanation of the regional differences of ventilation down the lung. Because of the weight of the lung, the intrapleural pressure is less negative at the base than at the apex. As a consequence, the basal lung is relatively compressed in its resting state but expands more on inspiration at the apex. (From West JB. *Ventilation/blood flow and gas exchange,* 5th ed. Oxford: Blackwell, 1990, with permission.)

Volumes vary directly with sitting height, explaining most differences between genders and races. Age tends to increase RV at the expense of VC. Note that because RV cannot be exhaled, neither RV nor any capacity that includes RV (TLC, FRC) can be measured by spirometry. Other techniques using gas equilibration or thoracic gas compression are required. The remaining volumes can be measured by a standard spirometer using a slow vital capacity maneuver. In modern clinical practice, spirometry has come to be synonymous with a forced vital capacity maneuver because this yields far more information about obstructive lung diseases, but an understanding of static lung volumes is fundamental to exploring the effects of pressure differentials and acceleration on the pulmonary parenchyma.

Inequality of Ventilation

With the partial exception of the larger airways, the lung is anything but rigid, and while the chest wall and the elastic recoil properties of the lung largely determine overall lung volumes, gravity plays a profound role in the relative expansion of different portions of the lung. In the upright individual, with gravity influencing the lung inside the chest cavity, intrapleural pressure is more negative at the apex than at the base, and the alveoli in the upper portion of the lung are significantly more distended than are those at the base. In essence, the lung is trying to "settle" toward gravity, and although the entire lung cannot move inferiorly due to a relatively rigid chest wall, the parenchyma will shift until restrained by its own internal elasticity. Compared with alveolar units in the lung bases, apical alveoli are functioning over a flatter portion of the lung pressure–volume curve; as a result, they experience a smaller change in volume with any given breath, and hence receive less ventilation. This is illustrated in Figure 2-2. That these changes are due to gravity rather than anatomy is demonstrated by the fact that, in the supine individual, the posterior portions of the lung are better ventilated, although the changes are less marked because of the smaller distances involved.

The relative compression of the basal portions of the lung has other effects. As subjects exhale below FRC, small airways in the bases begin to close, trapping air inside distal alveoli. The volume at which this occurs, known as *closing volume*, is close to RV in healthy young individuals, but because of loss of lung elasticity over time, closing volume rises with age and may even approach FRC. This probably accounts for most of the decrease in resting arterial oxygen tension with advancing age. As one would predict, single-breath nitrogen washout testing during weightlessness (parabolic flight) has documented an absence of dependent airway closure with zero gravity (1).

Because these effects are dependent on gravity, it would follow that sustained accelerative forces (defined as multiples of the Earth's gravity, or G) aggravate the topographic inequality in the lung. Dependent airway closure occurs routinely under G, and in combination with inequality of perfusion is responsible for a progressive decline in arterial oxygen levels with sustained acceleration. Ventilation with 100% oxygen partially offsets the hypoxia, but gives rise to a different problem, the syndrome of acceleration atelectasis (see Chapter 4). As noted earlier, airway closure in dependent lung parenchyma occurs before distal alveoli can collapse, which traps gas in those units. If 100% oxygen has been employed as the respirable gas mixture, the oxygen gradient from alveolus to pulmonary capillary will be such that the trapped gas is rapidly absorbed. (From the author's personal observations of intact animal preparations, the speed at which this occurs is remarkable.) The resulting atelectasis may cause dyspnea, retrosternal discomfort, and coughing. The use of less than 70% oxygen has been shown to prevent this syndrome (2).

Perfusion

Although the intent is to follow the course of oxygen through the process of respiration, a slight diversion is necessary. It is not possible to discuss gas flow to the lungs without discussing pulmonary blood flow, particularly because most causes of deficient oxygenation result from a failure to match perfusion to ventilation.

Pulmonary Vasculature

Pulmonary arteries, unlike pulmonary veins, are intimately associated with their respective airways, branching with each generation of the airways. This presumably facilitates the process of hypoxic pulmonary vasoconstriction. In a manner analogous to the airways, the total cross-sectional area in the pulmonary arterial bed increases progressively in the smaller vessels; for instance, the total surface area of the pulmonary capillaries is 50 times that of the pulmonary arterioles. This results in considerable slowing of blood flow velocity, allowing ample time for gas exchange.

The pulmonary circulation is a low-pressure system, the vessels displaying compliance characteristics more nearly akin to systemic veins than to systemic arteries. Indeed, under the microscope, small pulmonary arteries are difficult to distinguish from small pulmonary veins. The result is that the entire vascular bed in the lungs participates in blood volume redistribution in response to hypo- or hypervolemic states, and in response to hydrostatic pressure changes. For example, performance of a Valsalva maneuver may force half of the volume from the pulmonary vascular bed.

Inequality of Perfusion

If the lung has a relatively low degree of structural integrity, blood has essentially none, and is profoundly influenced by gravity. In the systemic circulation, the effect of gravity is largely counterbalanced by a high-pressure system, with vessels capable of withstanding such pressures. In the pulmonary circulation, the thinner structure and distensibility of the pulmonary arteries result in regional distribution of blood flow which is markedly influenced by gravity. Additionally, with an average distance of less than 0.5 μm between capillary blood and the alveolar space, pulmonary capillaries are minimally supported by surrounding tissue. The result is that capillary blood flow is also affected by intra-alveolar pressures, as well as by the pressure drop from arterial to venous sides. The lack of tissue support also puts the pulmonary capillaries at risk. Animal studies have shown that at a capillary transmural pressure of 40 mm Hg, disruption of vascular integrity occurs (3). Similar damage has been documented in cases of high-altitude pulmonary edema, and is felt to be etiologic to the disorder, the damage perhaps brought on by nonuniform hypoxic pulmonary vasoconstriction (4).

Average pulmonary arterial pressures (systolic 25 mm Hg, diastolic 8 mm Hg, mean 15 mm Hg) are just sufficient to perfuse the lung apices in the upright human, but the amount of flow to the apical segments is low. Blood flow increases in a roughly linear manner as one proceeds from the apex to the base. With exercise, blood flow increases throughout the lung, and differences are less marked. Under conditions of weightlessness, there appears to be a marked reduction in regional inequality of blood flow; measurements of pulmonary diffusing capacity (DL_{CO}) during a shuttle mission demonstrated dramatic improvement in DL_{CO}, which did not appear to be explained by increased pulmonary capillary blood volume (5). (Despite the name, changes in diffusing capacity more often reflect variations in the amount of wasted ventilation than changes in the alveolocapillary membrane.) In contrast, during sustained acceleration the regional differences in perfusion become more profound. At $+3\ G_z$ (an inertial force of three times the Earth's gravity, directed footward), the entire upper half of the lung is unperfused.

Another major determinant of regional inequality of pulmonary blood flow is hypoxic vasoconstriction. In contrast to systemic arteries, small pulmonary arteries constrict in response to hypoxia, but it is the intra-alveolar rather than the intraluminal oxygen tension that induces this response. Clearly a useful mechanism to blunt the hypoxemia that would otherwise occur with localized lung disease, hypoxic vasoconstriction occurs throughout the pulmonary vascular bed in response to environmental oxygen deficiency. In animal models, significant vasoconstriction has been shown to begin at an alveolar oxygen partial pressure (P_{AO_2}) of 70 mm Hg. In a healthy young adult, this would correspond to the expected P_{AO_2} at an altitude of 2,438 m (8,000 ft). Species differences do exist, and it is not known whether significant hypoxic vasoconstriction begins in the human at the same altitude, but it is worth noting that this represents the altitude above which high-altitude pulmonary edema begins to appear.

Ventilation—Perfusion Matching

With the topographic distribution of airflow and blood flow noted earlier, it should be evident that most of the gas exchange in the resting upright individual occurs in the bases of the lungs. Because gravity has a greater effect on blood flow, the ratio of ventilation to perfusion ($\dot{V}/\dot{Q}$ ratio) is maximal in the lung apices, and decreases as one proceeds to the bases. This is illustrated in Figure 2-3. The relative distributions of ventilation and perfusion result in a higher oxygen tension in the apical alveoli, which is thought to explain the proclivity of tuberculosis for the apices of the lungs.

Under normal conditions, the normal ventilation–perfusion inequalities merely result in a somewhat lower arterial oxygen partial pressure (Pa_{O_2}) than might otherwise be expected. During sustained acceleration, the mismatch of ventilation and perfusion becomes highly significant. As gravity increases, the lung shifts caudally, stretching the apical alveoli and compressing those in the bases. At higher levels of $+G_z$, many of the basal alveoli never open at all. At the same time, pulmonary blood flow is almost entirely redirected to the bases. At high levels of G, physiologic shunting may account for half the pulmonary blood flow. The drop in Pa_{O_2} is affected both by the intensity of $+G_z$ exposure, and by its duration. Even at $+3\ G_z$, arterial blood gases do not reach a steady state after several minutes of exposure (see Chapter 4).

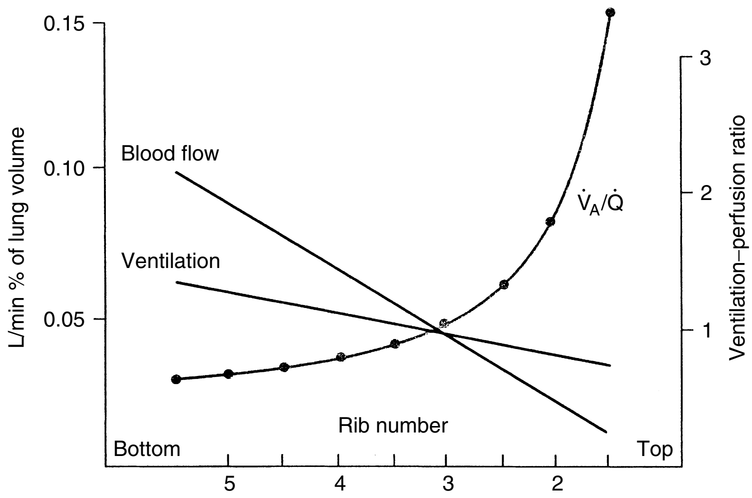


FIGURE 2-3 Distribution of ventilation and blood flow down the upright lung. Note that the ventilation–perfusion ratio decreases down the lung. (From West JB. *Ventilation/blood flow and gas exchange*, 5th ed. Oxford: Blackwell, 1990, with permission.)

Pulmonary Diffusion

The area of the gas exchange surface in the lung is huge, from 50 to 100 m^2, while the thickness of the membrane is usually under 0.5 μm. Diffusion is a passive process, determined in the case of a given gas by the difference in partial pressure across the membrane, by the diffusibility of the gas, and by the distance traversed. Diffusibility is a property of the gas itself, and is directly related to solubility, and inversely related to the square root of its molecular weight (see section Tissue Diffusion). Although carbon dioxide has a greater molecular weight than oxygen, it diffuses approximately 20 times as rapidly due to its much greater solubility. Pulmonary diffusion of carbon dioxide is not a limiting factor for gas exchange under any known circumstances. There are situations where oxygen diffusion limits pulmonary gas exchange, but in contrast to once-prevalent opinion, membrane thickness appears to rarely hamper oxygen diffusion even with diseased lungs. Under resting conditions oxygen equilibration between alveolar air and capillary blood is nearly complete before a third of the available time has elapsed. Therefore, there is enough of a reserve that equilibration can occur even when the membrane is thickened by interstitial disease, or when blood velocity increases with exercise. Diffusion limitation of oxygen may occur when both problems occur in combination, that is, exertion in the presence of interstitial lung disease. In the normal lung, diffusion limitation of oxygen only occurs in very hypoxic environments, particularly with exercise. At the summit of Mount Everest, for instance, diffusion limitation has been documented even at rest (6).

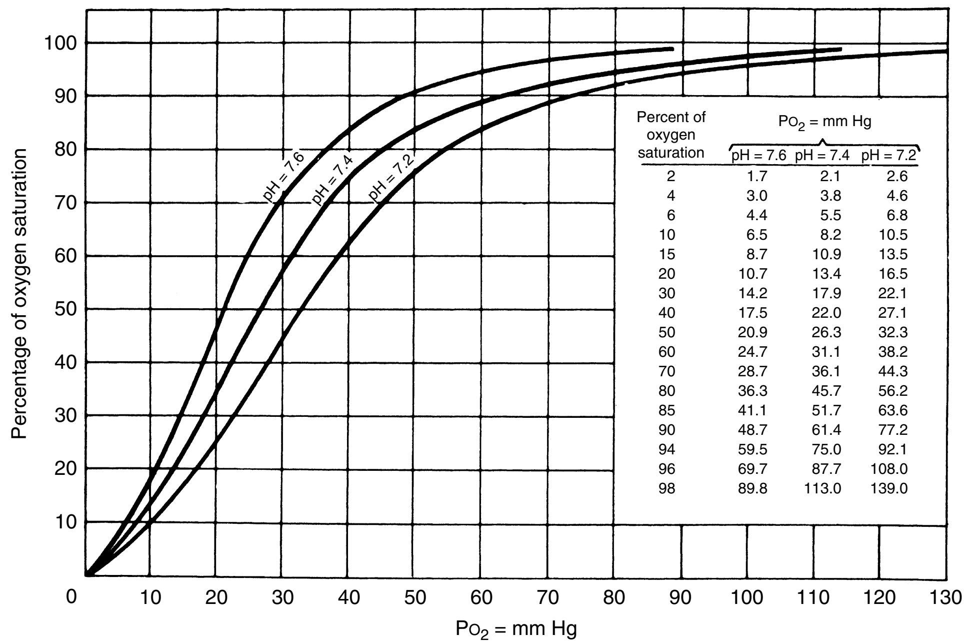
Gas Transport

Oxygen

Using Henry's Law, one should be able to estimate the amount of gas contained in the given volume of blood based on the partial pressure of the gas in the equilibrium atmosphere, the solubility of the specific gas in the liquid, and the temperature. In fact, in the case of oxygen and carbon dioxide, blood contains far more gas than predicted, because of chemical reactions that occur with the blood components. The amount of oxygen that is actually dissolved in plasma under normal conditions is almost negligible with respect to metabolic needs. The solubility of oxygen in blood is 0.003 mL 02/100 mL blood/mm Hg, so that even at sea level with a $Pa{O_2}$ of 100 mm Hg, 100 mL of arterial blood contains only 0.3 mL of oxygen. Ventilation with 100% oxygen, which typically results in a $Pa{O_2}$ of approximately 650 mm Hg, will raise the level of dissolved oxygen to approximately 2 mL 02/100 mL blood, which represents only approximately 40% of the amount of oxygen consumed at rest. In fact, 100 mL of blood at a $Pa{O_2}$ of 100 mm Hg actually carries approximately 21 mL of oxygen, nearly all of it complexed to a carrier molecule, hemoglobin. (Because hemoglobin is nearly oxygen saturated at that oxygen tension, a higher concentration of oxygen results in a relatively minor increase in oxygen transport, representing that dissolved in plasma.)

Hemoglobin is a complex substance, composed of a tetramer of polypeptide chains, each chain surrounding a single heme moiety, which is a protoporphyrin ring complexed with ferrous iron. The polypeptide chains consist of two α-chains and two slightly longer non-α chains; in normal adult hemoglobin A, the latter are designated as β chains. Single amino acid substitutions on the globin chains can result in marked differences in stability and oxygen affinity; for instance, a substitution of valine for glutamic acid on the β chains results in sickle cell disease. Each heme moiety can bind a single oxygen molecule, so that each hemoglobin molecule can carry up to four oxygen molecules. Each gram of hemoglobin can combine with 1.39 mL of oxygen so that ignoring the plasma content of dissolved oxygen, the oxygen-carrying capacity of 100 mL of blood is 20.8 mL 02, given a normal complement of 15 g of hemoglobin.

The tetrameric arrangement of hemoglobin is crucial, allowing rapid uptake and efficient delivery of oxygen over a narrow range of tensions. Monomeric forms such as myoglobin have a high affinity for oxygen but are incapable of releasing it except at very low oxygen tensions. In a tetrameric arrangement, the monomers interact such that the binding



Percent of oxygen saturation	PO_2 = mm Hg pH = 7.6	pH = 7.4	pH = 7.2
2	1.7	2.1	2.6
4	3.0	3.8	4.6
6	4.4	5.5	6.8
10	6.5	8.2	10.5
15	8.7	10.9	13.5
20	10.7	13.4	16.5
30	14.2	17.9	22.1
40	17.5	22.0	27.1
50	20.9	26.3	32.3
60	24.7	31.1	38.2
70	28.7	36.1	44.3
80	36.3	45.7	56.2
85	41.1	51.7	63.6
90	48.7	61.4	77.2
94	59.5	75.0	92.1
96	69.7	87.7	108.0
98	89.8	113.0	139.0

FIGURE 2-4 Oxyhemoglobin dissociation curves for human blood.

of the first oxygen molecule increases the affinity for oxygen of the remaining monomers. The physiologic result of this interaction is the sigmoidal oxygen dissociation curve seen in Figure 2-4.

The shape of the curve is physiologically advantageous. In the relatively flat upper portion of the curve, a fall of 30 to 40 mm Hg in PaO_2 from the "normal" level of 100 mm Hg, such as would occur at altitudes from 6,000 to 8,000 ft (1,829–2,438 m), results in only a 7% drop in arterial oxygen saturation. The curve accounts for some of the efficiency with which oxygen is loaded at the alveoli, because a large difference in partial pressure still exists when oxygen loading is nearly complete. The steepness of the lower portion of the curve means that a considerable amount of oxygen has been unloaded by the time the capillary oxygen tension has reached typical venous levels of 40 to 45 mm Hg. With a required oxygen tension at the mitochondrial level of 0.5 to 3 mm Hg, the large partial pressure difference between capillary and tissue facilitates diffusion into the tissues.

The actual position of the dissociation curve for normal hemoglobin A is influenced by temperature, by carbon dioxide tension, and by concentrations of hydrogen ion and intracellular 2,3-diphosphoglycerate; the last is a product of red cell metabolism, and increases in response to chronic hypoxia. A rise in any of these variables results in a shift of the curve to the right favoring oxygen unloading. The position of the dissociation curve is often expressed as the P50, the PO_2 at which 50% of oxygen is saturated; the normal value is approximately 27 mm Hg. Most of the effect of carbon dioxide on the oxygen dissociation curve, known as the *Bohr effect*, is actually mediated through pH change, but while the other factors shift the curve in response to particular situations such as exercise or chronic hypoxia, the Bohr effect is dynamic. As CO_2 is loaded at systemic capillaries the curve shifts rightward, resulting in further unloading of oxygen. Conversely, as CO_2 is off-loaded at the pulmonary capillary, the curve shifts leftward, favoring oxygen uptake.

Anemia reduces the oxygen-carrying capacity of blood in proportion to the reduction of hemoglobin. However, loss of hemoglobin through oxidation of the ferrous iron to the ferric form (methemoglobin), or through complexing with carbon monoxide (carboxyhemoglobin), causes an impairment of oxygen transport disproportionate to the loss of available hemoglobin. In both cases, the dissociation curve for the remaining hemoglobin shifts leftward, impairing off-loading of oxygen from that hemoglobin which is still available for transportation.

In the resting adult, the systemic circulation off-loads approximately 5 mL O_2 per 100 mL, resulting in a mixed venous PO_2 of approximately 50 mm Hg and an oxygen saturation of 75%. With a system relying on passive diffusion there are limits to how much oxygen can be extracted, but a mixed venous saturation of 75% means a considerable amount of oxygen remains as a reserve. On the basis of an average resting cardiac output of 5 L/min, the total oxygen consumption calculates to be 250 mL O_2/min in the 70-kg adult. Moderately active young men are able to increase their oxygen consumption to approximately 3 L/min (with up to 5 L/min in world class athletes), but cardiac output is incapable of matching this demand. With increased oxygen demand during maximal exercise, increased cardiac output accounts for approximately one third of the excess demand with the remainder being met by increased oxygen extraction from hemoglobin and a corresponding fall in mixed venous saturation.

The heart is in a unique situation regarding oxygen extraction. Even at rest, the myocardium removes approximately 12 mL oxygen per 100 mL blood. Therefore, blood in the coronary sinus has a residual oxygen content of 8 mL per 100 mL blood, corresponding to a PO_2 of 18 mm Hg. (Of course, the heart is never really at rest, which accounts for some of the difference compared with systemic venous blood.) Increased demand must be met by increased coronary blood flow, which is largely mediated through coronary vasodilation. In the left ventricle, increases in coronary perfusion are limited by the fact that flow can only occur during diastole, and exercise-induced tachycardia limits the available time. Undoubtedly, these limitations play a role in the cardiac reserve available for periods of exertion.

Carbon Dioxide

Because carbon dioxide is much more soluble than oxygen in blood, with a solubility of 0.0697 mL CO_2/100 mL plasma/mm Hg, or approximately 24 times that of oxygen, dissolved carbon dioxide constitutes an appreciable percentage (approximately 10%) of the total elimination. Carbon dioxide, like oxygen, also undergoes chemical reaction with blood components, forming bicarbonate, which is responsible for approximately 60% of CO_2 excretion, and combining with proteins to form carbamino compounds, which account for the remaining 30%.

Carbonic anhydrase catalyzes the hydration of CO_2 to carbonic acid, which then readily forms hydrogen ion and bicarbonate. Most of the evolution of bicarbonate occurs within erythrocytes because carbonic anhydrase is absent from plasma. Bicarbonate moves into plasma by exchange with chloride. Within the erythrocyte, some of the hydrogen ions are bound to hemoglobin with the desaturated form proving to be the more efficient proton acceptor. Therefore, the off-loading of oxygen at the systemic capillary encourages the formation of bicarbonate, which reduces carbon dioxide tension, and increases its uptake. This mechanism is known as the *Haldane effect*. Desaturated hemoglobin also aids CO_2 transport through another process. Globins are the most important substrate for the formation of carbamino compounds, and oxygen desaturation enhances this reaction, which again facilitates the further uptake of CO_2 at the systemic capillary.

Nitrogen

Nitrogen is biologically inert, undergoing no chemical reaction with blood. Its concentration is determined by Henry's Law, being directly proportional to the partial pressure of nitrogen in the adjacent gas. The actual content is also determined by the solubility of the gas, which in plasma at body temperature is 0.0088 mL N_2/100 mL/mm Hg pN_2, approximately three times that of oxygen. Nitrogen is five times more soluble in fat than in plasma, an observation that partially accounts for nitrogen acting as an anesthetic at high partial pressures, as demonstrated by the development of nitrogen narcosis during diving. The differential solubility also plays a role in decompression sickness (DCS) because different tissues with equivalent partial pressures of nitrogen contain different amounts of the gas (see Chapter 3).

Tissue Diffusion

There exist approximately 50 billion capillaries in the human body, with a combined cross-sectional area more than a thousand times the cross-sectional area of the aorta. This ensures a slow enough flow to allow adequate time for exchange of gases and nutrients. It is rare for a cell to be more than 30 to 50 μm from the nearest capillary. This distance is considerably greater than the 0.5 μm between the alveolus and the capillary, but the latter's role is to provide gas exchange for the entire organism, and the pulmonary process must be more efficient.

The exchange of oxygen from capillaries to cellular mitochondria occurs along a gradient. Fick's Law of diffusion describes the rate of transfer of a gas through a tissue as inversely proportional to thickness (T), and directly proportional to tissue area (A), partial pressure difference, and a constant, D.

$$Vgas = A/T \times D(P_1 - P_2)$$

The value of the constant D is dependent upon the particular gas and tissue because it is directly proportional to the solubility of the gas in the tissue, and inversely proportional to the square root of the molecular weight of the gas.

To increase diffusion of oxygen into tissues, the systemic circulation can respond by increasing the flow through capillaries, which increases the partial pressure gradient $(P_1 - P_2)$ for oxygen diffusion at the distal portion of the capillary. More importantly, it can also increase the number of open capillaries, which increases the area (A) for diffusion, and decreases the distance, or thickness (T), which the gas traverses. The recruitment or rarefaction mechanism seems to be constantly operative, with terminal arterioles fluctuating in their level of resistance as local tissue demands change. Decreasing oxygen tension, rising carbon dioxide tension, and falling pH all stimulate perfusion of local systemic capillary beds. There appear to be considerable differences between organs, both with respect to the potential recruitment of capillaries, and with respect to the major stimulus. The brain appears to be particularly sensitive to the tension of carbon dioxide, and there is relatively little difference in capillary flow between rest and exercise. Coronary blood flow to cardiac muscle appears to be most sensitive to oxygen tension, but capillary recruitment is limited by the diastolic interval, as noted earlier. In the renal and splanchnic circulations, flow decreases in response to exercise, as it does in muscle groups that are not involved with exertion. In actively exerting muscle groups, local endothelial control in response to oxygen and carbon dioxide tensions and to pH overrides sympathetic stimulation, resulting in striking recruitment of capillaries and increased local circulation.

Cellular Utilization

Approximately 95% of oxygen consumption by individual mammalian cells involves direct oxidation of substrates by the mitochondrial cytochrome system, in the process known as *oxidative phosphorylation*. The oxidative process is vital for the production of energy. Production of adenosine triphosphate (ATP), the common coin of intracellular energy transactions, is possible in the absence of oxygen, but the initial step in carbohydrate metabolism, the cytosolic conversion of glucose to pyruvic acid through the glycolytic pathway, is inefficient, releasing only two molecules of ATP for each molecule of glucose. In the absence of oxygen, pyruvic acid is converted into lactic acid, which as a waste product is far more difficult to excrete than carbon dioxide. Furthermore, the process is incapable of catabolizing fatty or amino acids. The uptake of pyruvic acid into the mitochondrion, with its ensuing catabolism through the Kreb's cycle and oxidative phosphorylation, yields an additional 36 molecules of ATP, with the production of carbon dioxide and water. The former is excreted rapidly, and the latter is commonly beneficial; in certain desert animals the metabolic production of water functions as a significant source of hydration. The aerobic catabolic pathway is illustrated in Figure 2-5.

The electron transport system involved in the reduction of oxygen is tightly linked so that free radicals are not usually released into the cytosol. The intracellular oxygen tension required by the mitochondrion is only approximately 3 mm Hg, and values above this do not affect the rate of oxygen uptake. Additional energy requirements are met not by increased mitochondrial activity, but rather by additional

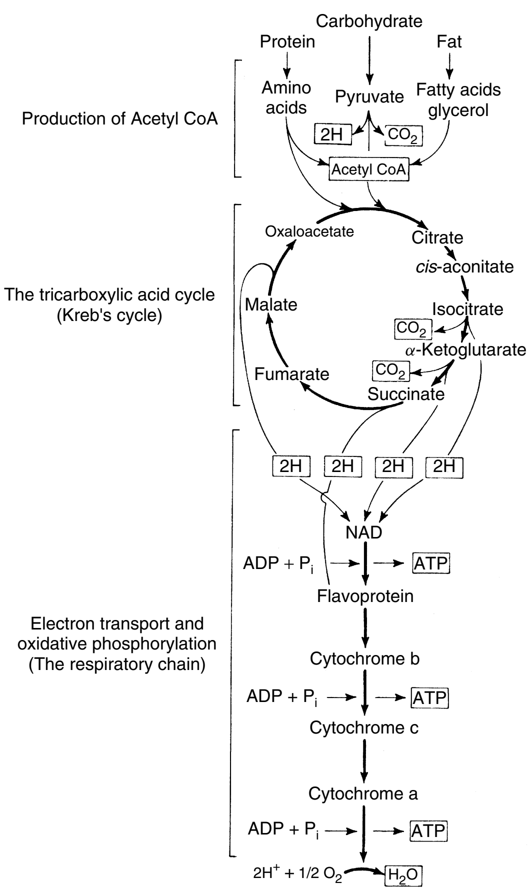


FIGURE 2-5 Cellular respiration. ADP, adenosine diphosphate; ATP, adenosine triphosphate.

numbers of mitochondria. A small lymphocyte will have only a few mitochondria, whereas a hepatocyte typically possesses approximately a thousand. Curiously, the cell responsible for the transportation of oxygen is the cell with the least use for it, because erythrocytes lose their mitochondria as well as their nuclei as they mature; erythrocytes are obligate anaerobes, utilizing glycolysis to meet their minor metabolic needs.

During oxidative catabolism, the ratio of carbon dioxide released to oxygen consumed is known as the *respiratory exchange ratio*, or respiratory quotient (RQ, or simply R). Catabolism of carbohydrates results in an RQ of 1.0; fatty acids and amino acids release less carbon dioxide relative to oxygen consumption, and have an RQ of approximately 0.7. Because diets are generally a mixture of all three components, the RQ usually averages between 0.80 and 0.85.

Control of Ventilation

Ventilatory control is maintained through a feedback control mechanism comprising a controller, the central nervous system (CNS); effectors, the muscles of respiration; and a number of sensors. The mechanism is linked between sensors and controller by afferent neurons and between controller and effectors by efferent neurons. Although the primary controller is located in the brainstem, it can be at least partially overridden by instructions from the cerebral cortex. The sensors are designed to detect changes in blood chemistry (chemoreceptors), or physical distortion of the lungs or chest wall (mechanoreceptors).

Cardiac rhythm is determined by a group of pacemaker cells whose unstable transmembrane potential results in spontaneous electrical activity, but if such a focus exists in the ventilatory controller it has never been identified. The rhythmic pattern of ventilation appears to depend on interconnected neurons in the medulla and pons; the actual generation and maintenance of rhythmic inspiration is likely determined by reciprocal impulses between these centers. Medullary centers consist of the dorsal respiratory group, which is active during inspiration, and the ventral respiratory group, different portions of which are active during inspiration and expiration. In addition, the ventral group contains neurons innervating upper airway muscles and bronchial smooth muscles. The pontine apneustic and pneumotaxic centers appear to influence respiratory timing. Experimental damage to the pneumotaxic center, in combination with vagotomy, induces an apneustic breathing pattern (prolonged inspiration), which disappears with wakefulness, and returns with sleep.

Ventilatory control is complex, and is affected by a number of inputs. Coordination of the respiratory muscles is required for the primary task of maintaining respiratory homeostasis and activities such as phonation, defecation, and parturition to name a few. While these activities are controlled by the cortex and brainstem, the intrinsic ventilatory rate is influenced most significantly by input from chemoreceptors. Under normal conditions, carbon dioxide tension is the primary driver for changes in ventilation. Changes in arterial carbon dioxide tension (Pa_{CO_2}) are sensed predominantly by central chemoreceptors, with a small input from peripheral chemoreceptors. The location of the central chemoreceptors is unclear although they appear to be distinct from the respiratory centers described earlier. Stimulation of the central chemoreceptors appears to be largely mediated by a decrease in the pH of brain interstitial fluid. The process is a smooth one; increases in Pa_{CO_2} induce a linear increase in minute ventilation, first by increasing the depth and then the rate of ventilation. Decreases in Pa_{CO_2} depress ventilation; one can induce apnea in the sleeping or anesthetized individual through artificial hyperventilation.

It may seem counterintuitive that normal chemoreceptor input is based on carbon dioxide tension rather than oxygen tension but it is actually reasonable. Ventilation plays a minute-to-minute role in maintaining acid–base balance, whereas in healthy individuals the oxyhemoglobin dissociation curve ensures adequate arterial oxygen saturation despite such respiratory variation. This situation pertains unless oxygen tension reaches 60 mm Hg. From that point there is a rapid increase in minute ventilation in response to further reductions in Pa_{O_2}. Therefore, unlike the linear increase in ventilation with rising Pa_{CO_2}, there is a hyperbolic increase in ventilation with a falling Pa_{O_2}. The response is affected by Pa_{CO_2}, with a greater response to hypoxemia under hypercapnic conditions (7). The effect of different carbon dioxide tension on the hypoxic ventilatory response is displayed Figure 2-6.

The input from peripheral chemoreceptors is well illustrated by previously normal patients presenting with pneumonia. Those with milder cases and room air oxygen tensions

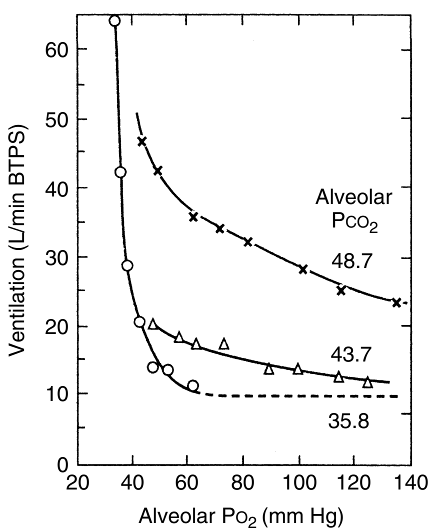


FIGURE 2-6 Hypoxic response curves. Note that when the P_{CO_2} is 35.8 mm Hg, almost no increase in ventilation occurs until the P_{O_2} is reduced to approximately 50 mm Hg. BTPS, body temperature and pressure, saturated with water vapor. (Modified by West JB Respiratory Phisiology, 2nd ed. Lippincott Williams & Wilkins, 1979, with permission; From Loeschke HH, Gertz KH. Einfluss des O2-Druckes in der Einatmungsluft auf die Atemtätigkeit der Menschen, geprüft unter Konstanthaltung des alveolaren CO2-Druckes. *Pflugers Arch* Ges *Physiol* 1958;267:460–477.)

reduced to 65–85 mm Hg will typically have near-normal pH and Pa_{CO_2} values. However, if the ventilation-perfusion mismatching is severe enough that the eupenic Pa_{O_2} would be reduced below about 60 mm Hg, then the usual pattern seen on arterial blood gases is a Pa_{O_2} maintained (if possible) near 60 mm Hg, with hyperventilation and respiratory alkalosis. Administration of supplemental oxygen typically raises the Pa_{O_2} and allows the return of Pa_{CO_2} and pH to more normal values.

The sensors responsible for this "hypoxic override" reside in the carotid and aortic bodies, innervated by the glossopharyngeal and vagal nerves respectively. These constitute the peripheral chemoreceptors. The carotid bodies, which appear to be more important in the human, also respond to changes in Pa_{CO_2} and pH. Physiologic responses to hypoxia seem to be entirely confined to these peripheral chemoreceptors, because in their absence hypoxia actually depresses respiration. The high arterial blood supply through the carotid allows carotid body oxygen needs to be met by dissolved plasma oxygen. As a result, Pa_{O_2} rather than oxygen content is the signal sensed by the chemoreceptor. This explains why anemia and carbon monoxide poisoning, which are accompanied by low arterial oxygen content but normal oxygen tension, generally fail to elicit tachypnea.

Abnormal Ventilation

Ventilation is so closely tied to arterial carbon dioxide tension that hypoventilation and hyperventilation are usually considered to be synonymous with hypercarbia and hypocarbia, respectively. This construction is occasionally misleading. For instance, the patient with obstructive lung disease and carbon dioxide retention actually has increased minute ventilation, although the volume of effective ventilation is depressed. Nonetheless, carbon dioxide is closely linked to ventilation, and relatively immune from other influences, for several reasons. Unlike oxygen, the amount of environmental CO_2 is negligible with rare exceptions so that Pa_{CO_2} is determined by the rate of production and loss of carbon dioxide. While production of CO_2 definitely increases with conditions such as exercise, respiratory drive is modulated by Pa_{CO_2}, and under normal conditions an increase in production of CO_2 is matched by an increase in ventilation. Lastly, lung abnormalities that might raise Pa_{CO_2} can be effectively countered by increased ventilation. Because CO_2 is either carried in solution, or readily released through dissociation of bicarbonate or carbamino compounds, inadequate regional gas exchange in the lung can, in the case of carbon dioxide, be compensated by overventilating other areas of the lung. The result of such compensated ventilation–perfusion mismatching is that systemic Pa_{CO_2} levels are normal or even low. In contrast, arterial oxygen tensions in such situations cannot be made normal through increasing ventilation; blood traversing ventilated regions of the lung cannot carry more than approximately 21 mL/O_2/100 mL (i.e., saturated hemoglobin), regardless of how much ventilation is increased, and therefore cannot fully compensate for the low oxygen content of blood traversing poorly ventilated sections of lung.

Hypercapnia

With the exception of severe lung disease with $\dot{V}/\dot{Q}$ mismatching so severe that it cannot be fully compensated, hypercapnia in clinical practice is usually seen only with hypoventilation due to primary respiratory failure. This occurs either due to a state of altered consciousness, such as drug-induced sedation, or to muscular disease. Such problems are rare in the practice of aerospace medicine.

Oddly, where hypercapnia is typically of concern to aerospace medicine represents an exception to an earlier observation. Environmental carbon dioxide levels are usually negligible, but there is a distinct risk in a closed environment such as a sealed cabin in space flight vehicles (see Chapter 10). Even minor elevations in CO_2 concentration result in a prompt increase in ventilation. The result is to keep arterial $Paco_2$ stable, but this becomes progressively more difficult as inspired CO_2 tensions approach 40 mm Hg, equivalent to approximately 5.6% CO_2 at sea level. Above that point, $Paco_2$ begins to rise, with ventilation continuing to increase until it plateaus at a $Paco_2$ of 80 to 100 mm Hg. Further increases in carbon dioxide tension lead to altered consciousness, and eventually death. In closed-loop systems such as aboard spacecraft, CO_2 is removed by chemical reaction with lithium hydroxide or by reversible absorption systems. The allowable $PIco_2$ limit for shuttle missions is 7.6 mm Hg. The National Aeronautics and Space Administration (NASA) long-term spacecraft maximum allowable concentration (SMAC) is 5.3 mm Hg for 7-, 30-, and 180-day exposures.

Hyperventilation

To all intents and purposes, hypocapnia is equivalent to hyperventilation, because CO_2 production does not appreciably drop below baseline and environmental CO_2, normally close to zero, can hardly fall lower. The symptoms and signs of hyperventilation are mediated through the combined effects of alkalemia, which notably results in a fall in serum calcium due to increased protein binding, and the hypocarbia itself, which results in cerebral vasoconstriction. A sense of generalized weakness is a common complaint, often accompanied by a sense of impending doom. Neuromuscular manifestations typically include dysesthesias and paresthesias about the mouth, hands, and feet, as well as muscular cramping. Severe hyperventilation can result in tetany, seizures, or syncope.

Carbon dioxide is in equilibrium with serum bicarbonate through the intermediate formation of carbonic acid, as follows:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

A sudden drop in $Paco_2$ causes the reaction to proceed to the left by the law of mass action, resulting in the loss of hydrogen ions through combination with bicarbonate. The resulting respiratory alkalosis is buffered to an extent by tissues and by lactic acid production, but renal compensation is too slow to have much effect in acute hyperventilation.

Hyperventilation is a significant issue in aerospace medicine. Primary hyperventilation can occur in response to psychological or physical stress, or in response to drugs such as salicylates, progestins, or theophylline. Hyperventilation may also occur in response to pressure breathing. The usual diagnostic dilemma lies in sorting out such pure hyperventilation from secondary hyperventilation occurring in response to hypoxia. As noted earlier, a Pao_2 below 60 mm Hg typically results in hyperventilation. As a rule, this response is only partially effective in raising arterial oxygen tension, but carbon dioxide is unloaded as efficiently as ever. The difficulty is that many of the more noticeable symptoms of hypoxia, for example, circumoral and acral paresthesias, are actually due to hypocarbia. Those signs or symptoms that may specifically be due to hypoxia, such as alterations in color vision or impaired mental status, are more difficult to detect and furthermore the decreased cerebral perfusion that accompanies significant hypocarbia may also affect vision or mental status. Cyanosis is not a feature of primary hyperventilation, but in the cold environment typical of high altitudes, stagnant hypoxia in the extremities may cause local cyanosis. The similarities between primary hyperventilation and hypoxia are displayed in Table 2-2.

In clinical practice, primary hyperventilation is treated by reassurance to reduce the rate and depth of breathing, and by rebreathing exhaled air. At altitude, however, the strong

TABLE 2-2

Comparison of Hyperventilation and Hypoxic Hypoxia Syndromes

Signs and Symptoms	*Hyperventilation*	*Hypoxia*
Onset of symptoms	Gradual	Rapid (altitude dependent)
Muscle activity	Spasm	Flaccid
Appearance	Pale, clammy	Cyanosis
Tetany	Present	Absent
Breathlessness	X	X
Dizziness	X	X
Dullness and drowsiness	X	X
Euphoria	X	X
Fatigue	X	X
Headache	X	X
Poor judgment	X	X
Lightheadedness	X	X
Faulty memory	X	X
Muscle incoordination	X	X
Numbness	X	X
Performance deterioration	X	X
Increased respiratory rate	X	X
Delayed reaction time	X	X
Tingling	X	X
Unconsciousness	X	X
Blurred vision	X	X

X means that the sign or symptom can occur in either condition.

possibility that any such symptoms may represent hypoxia mandates a different approach. The aviator should first treat possible hypoxia, by administering 100% oxygen under pressure, before attempting to decrease the rate and depth of breathing. Oxygen supplementation is harmless in the setting of primary hyperventilation, and potentially life-saving for altitude hypoxia. Appropriate treatment of a hypoxic episode is discussed in the following section. The ultimate diagnosis is usually determined by a thorough ground check of the aircraft's life support equipment.

Abnormal Oxygenation

With the complexity of the oxygen delivery system, hypoxia at the tissue level may be caused by any of a number of abnormalities in uptake, transport, or utilization. Hyperoxia on the other hand is an artificially induced condition with the physiologic effects dominated by oxygen toxicity.

Hypoxia

Anaerobic metabolism in the human is inefficient and cannot be sustained for any period of time. Except for mature erythrocytes, all tissues require a more or less steady supply of oxygen, with the CNS being particularly susceptible to states of deficiency. As an example, cerebral resuscitation is seen as the immediate goal of cardiopulmonary life support, because cardiac arrest lasting longer than 3 minutes commonly causes CNS damage. Compared with anoxia, hypoxia causes more subtle deficiencies, but reduced visual function, cognitive impairment, and eventually altered consciousness are the principal manifestations.

Four types of hypoxia are recognized, and are discussed in order of increasing importance in aerospace medicine.

Histotoxic Hypoxia

Characterized by inability of the cell to use delivered oxygen, histotoxic hypoxia is usually due to poisoning of the cytochrome oxidase system. Cyanide is the prototype toxin. Carbon monoxide primarily acts through hypemic hypoxia but because it successfully competes with oxygen for cytochrome c oxidase when tissue oxygen tension is low, it also induces a degree of histotoxic hypoxia. Arterial oxygen tension is normal with histotoxic hypoxia, and cyanosis is absent.

Hypemic Hypoxia

Hypemic hypoxia results from a reduction in oxygen-carrying capacity by the blood. Anemia will cause a decrease in carrying capacity directly proportional to the reduction in hematocrit. A more complex, and probably more pertinent, cause of hypemic hypoxia is carbon monoxide poisoning. Carbon monoxide (CO), the leading cause of accidental poisoning in the United States, is the product of incomplete combustion and is present in aircraft exhaust fumes as well as cigarette smoke. The principal effect of CO poisoning is hypemic hypoxia, through two mechanisms. Like oxygen, CO binds hemoglobin reversibly, but it does so with an affinity more than 200 times that of oxygen, rendering those molecules of bound hemoglobin temporarily unusable. Furthermore, through the interrelated nature of the hemoglobin tetramer, the oxygen affinity of the remaining unbound hemoglobin is altered; the result is that the O_2 disassociation curve is shifted to the left, and peripheral oxygen release is impaired. Because CO is bound reversibly to hemoglobin, treatment of more than minimal poisoning consists of oxygen therapy. One hundred percent oxygen reduces the half-time for CO elimination from about 4 hours to 1 hour, while hyperbaric oxygen at 2.5 ATA (atmospheres absolute) decreases it to approximately 30 minutes.

In hypemic hypoxia, PaO_2 is normal, although content is considerably reduced. Except for the rare case of methemoglobinemia, cyanosis is unusual; deoxyhemoglobin is in short supply with anemia, while carboxyhemoglobin is actually a cherry red color.

Stagnant Hypoxia

Inadequate blood flow, whether systemic or regional, may result in stagnant hypoxia to the affected tissue. Arterial oxygen tension and cyanosis are both variable. The common clinical causes, such as shock or peripheral vascular disease, are unlikely to be of concern to the flight surgeon, but two examples of stagnant hypoxia are of particular interest. DCS (see Chapter 3) causes localized stagnant hypoxia due to bubble formation. Sustained acceleration (covered in Chapter 4) induces pooling of blood in dependent areas, with stagnant hypoxia at the opposite end of the G axis. Because $+G_z$ is the force most likely to be encountered, the brain, the organ least likely to tolerate transient ischemia, is the one most often subjected to it under sustained acceleration.

Hypoxic Hypoxia

Hypoxic hypoxia, a deficiency in alveolar oxygenation, is the most common cause of hypoxia clinically, and is far and away the most common cause in aviation. In clinical medicine, the etiology is occasionally inadequate ventilation, but more often improper matching of ventilation to perfusion. In aviation medicine, the cause is more likely to be reduction in the oxygen partial pressure in inspired air. In either case, PaO_2 is reduced, and cyanosis is often present. The remaining discussion of hypoxia will focus on a subcategory of hypoxic hypoxia, that is, altitude hypoxia.

Altitude Hypoxia

Hypoxia is of physiologic importance anytime humans exceed approximately 3,048 m (10,000 ft) altitude. This is true even for those who chronically live at such altitudes, although the physiologic considerations with chronic altitude exposure differ from those with acute exposure. It is important not to extrapolate the effects of altitude hypoxia from the highland to the lowland dweller, because altitude acclimatization profoundly affects human tolerance. A sea level dweller ascending suddenly to the summit of Mt. Everest [8,882 m (29,141 ft)] would be unconscious within a few minutes, and dead soon afterward, yet mountaineers have managed to carry out intense exertion at that altitude without oxygen. Because aviation systems attempt to maintain oxygen tensions equivalent to 10,000 ft or less, and hypoxic episodes are usually acute exposures due to equipment failure, the effects of chronic altitude exposure will not be discussed in detail.

Barometric pressure varies in a nonlinear manner with altitude, due to the compressibility of air. By Dalton's Law, and given thorough mixing of gases in the homosphere, atmospheric partial pressure of oxygen will vary in the same manner. Table 2-3 shows total air pressure and oxygen pressure at 1,000-ft increments of altitude while breathing ambient air, up to an altitude of 7,620 m (25,000 ft). It also displays representative values while breathing 100% oxygen at altitudes of 10,058 to 14,041 m (33,000–46,000 ft).

Partial pressure of oxygen in alveoli is lower than the corresponding ambient P_{O_2} because of the displacement of oxygen by water vapor and because of exchange for carbon dioxide. Alveolar oxygen tension (P_{AO_2}) is calculated using the alveolar gas equation:

$$P_{AO_2} = P_{IO_2} - P_{ACO_2}/R + [P_{ACO_2} \times F_{IO_2} \times 1 - R/R]$$

R is the respiratory quotient, which is usually taken to be 0.85. P_{ACO_2} is the mean alveolar carbon dioxide pressure, which equals arterial CO_2 tension (P_{aCO_2}). P_{IO_2} is the partial pressure of inspired oxygen, which is calculated as:

$$P_{IO_2} = (P_B - P_{H_2O})F_{IO_2}$$

where P_B is ambient barometric pressure, F_{IO_2} is the fraction of inspired oxygen, and P_{H_2O} is water vapor pressure [47 mm Hg at body temperature and pressure, saturated

TABLE 2-3

Respiratory Gas Pressures and Gas Exchange Ratios

Altitude (m)	*Altitude* (ft)	*Pressure* (psia)	*Pressure* (mm Hg)	*Ambient* P_{O_2} *(mm Hg)*	P_{AO_2} *(mm Hg)*	P_{ACO_2} *(mm Hg)*	P_{H_2O} *(mm Hg)*	*Respiratory Exchange Ratio (R)*
Breathing Air								
0	0	14.69	759.97	159.21	103.0	40.0	47.0	0.85
305	1,000	14.17	733.04	153.57	98.2	39.4	—	—
610	2,000	13.66	706.63	148.04	93.8	39.0	—	—
914	3,000	13.17	681.23	142.72	89.5	38.4	—	—
1,219	4,000	12.69	656.34	137.50	85.1	38.0	—	—
1,524	5,000	12.23	632.46	132.50	81.0	37.4	47.0	0.87
1,829	6,000	11.77	609.09	127.60	76.8	37.0	—	—
2,134	7,000	11.34	586.49	122.87	72.8	36.4	—	—
2,438	8,000	10.91	564.64	118.29	68.9	36.0	—	—
2,743	9,000	10.50	543.31	113.82	65.0	35.4	—	—
3,048	10,000	10.10	522.73	109.51	61.2	35.0	47.0	0.90
3,353	11,000	9.72	502.92	105.36	57.8	34.4	—	—
3,658	12,000	9.34	483.36	101.26	54.3	33.8	—	—
3,962	13,000	8.99	464.82	97.38	51.0	33.2	—	—
4,267	14,000	8.63	446.53	93.55	47.9	32.6	—	—
4,572	15,000	8.29	429.01	89.88	45.0	32.0	47.0	0.95
4,877	16,000	7.96	411.99	86.31	42.0	31.4	—	—
5,182	17,000	7.65	395.73	84.50	40.0	31.0	—	—
5,486	18,000	7.34	379.73	79.55	37.8	30.4	—	—
5,791	19,000	7.05	364.49	76.36	35.9	30.0	—	—
6,096	20,000	6.76	349.50	73.22	34.3	29.4	47.0	1.00
6,401	21,000	6.48	335.28	70.24	33.5	29.0	—	—
6,706	22,000	6.21	321.31	67.31	32.8	28.4	47.0	1.05
7,010	23,000	5.95	307.85	64.49	32.0	28.0	—	—
7,315	24,000	5.70	294.89	61.78	31.2	27.4	—	—
7,620	25,000	5.46	282.45	59.17	30.4	27.0	47.0	—
Breathing 100% Oxygen[a]								
10,058	33,000	3.81	197.10	197.10	109	40	47.0	—
10,973	36,000	3.30	170.94	170.94	85	38	47.0	—
11,887	39,000	2.86	148.08	148.08	64	36	47.0	—
12,192	40,000	2.73	141.22	141.22	—	—	—	—
12,802	42,000	2.48	128.27	128.27	48	33	47.0	—
13,716	45,000	2.15	111.25	111.25	34	30	47.0	—
14,021	46,000	2.05	105.92	105.92	30	29	47.0	—

([a]From Holmstrom FMG. Hypoxia. In: Randall HW, ed. *Aerospace medicine*. Baltimore: Williams & Wilkins, 1971, with permission.)

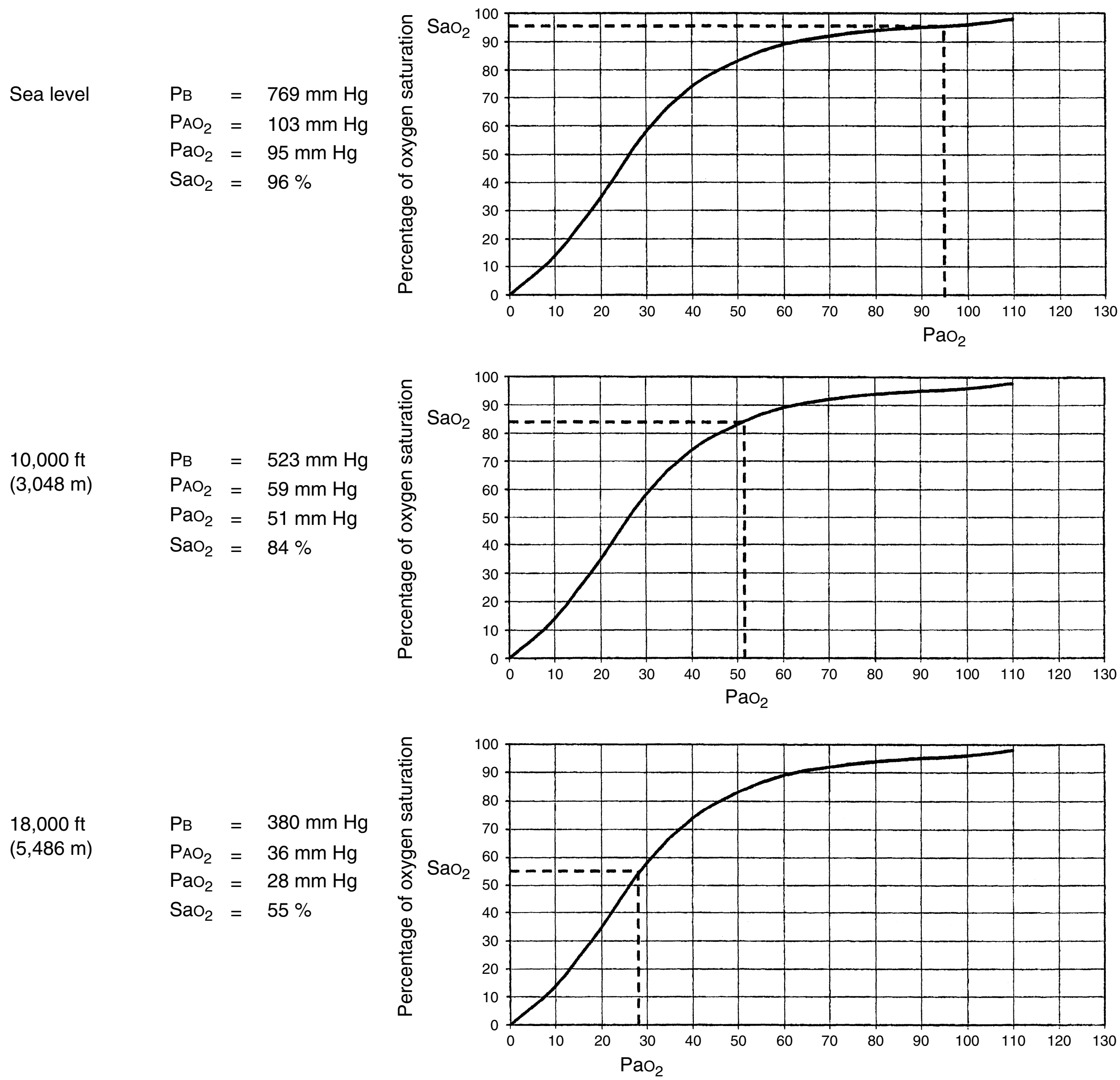


FIGURE 2-7 Expected oxyhemoglobin saturation at representative altitudes in normal individuals breathing ambient air.

with water vapor (BTPS)]. Because the term in brackets is small on ambient air (~2 mm Hg), it is usually ignored, and the equation may be written:

$$P_{AO_2} = (P_B - 47)F_{IO_2} - P_{aCO_2}/R$$

Table 2-3 also displays the corresponding alveolar oxygen and carbon dioxide tensions at the given altitudes. The table ends at 25,000 ft for ambient air, and 46,000 ft for 100% oxygen; above these altitudes alveolar oxygen tensions cannot be calculated because altered consciousness supervenes before a steady state can be reached.

Although alveolar and arterial carbon dioxide tensions are essentially identical, arterial oxygen tension is slightly lower than alveolar oxygen tension because of imperfect matching of ventilation and perfusion. This alveolar–arterial (A–a) gradient for oxygen is approximately 8 mm Hg in a healthy young person, although it gradually rises with age, and may be markedly elevated with lung disease. Figure 2-7 shows the expected levels of hemoglobin saturation at three different altitudes, assuming normal hemoglobin, an RQ of 0.85, and a normal alveolar–arterial gradient of 8 mm Hg. At a height of 3,048 m (10,000 ft), Pao_2 would measure approximately 51 mm Hg, yielding a saturation of approximately 84%. Note that this is just entering the steep portion of the dissociation curve. At 5,486 m (18,000 ft), Pao_2 has fallen to 28 mm Hg, and oxyhemoglobin saturation has dropped to 55%, which is lower than normal mixed venous saturation. Actually, it is unlikely that the A–a gradient remains stable with altitude. With elevated pulmonary artery pressures, ventilation–perfusion matching appears to be more uniform, but because at higher altitudes diffusion begins to be a limiting factor, the end result is likely to be no net change.

Effects of Hypoxia

Acute altitude hypoxia affects critical organ systems in different manners. The respiratory and cardiovascular systems, which in the healthy individual are reasonably tolerant of moderate deficiencies of oxygen, respond by attempting to increase oxygen delivery, whereas the CNS becomes more or less dysfunctional as a result of oxygen deficiency.

The response of the respiratory system hinges on the peripheral chemoreceptors, the carotid and aortic bodies discussed earlier. The effect of acute exposure to altitude on ventilation is displayed in Table 2-4. Ventilatory response to hypoxia is not limited by effort, because maximum voluntary ventilation typically exceeds 100 L/min in healthy individuals. Instead, respiratory stimulation due to hypoxia is blunted by falling carbon dioxide levels. The effect of different carbon dioxide tensions on the hypoxic ventilatory response is displayed in Figure 2-6.

The cardiovascular response to altitude hypoxia is to increase cardiac output. The volume of oxygen extracted from the systemic circulation (oxygen consumption) is a product of the rate of delivery (cardiac output) and the proportion of oxygen off-loaded (the arteriovenous oxygen difference). As noted earlier, increased oxygen demand such as with exercise is usually met by increasing both cardiac output and oxygen extraction. However, mixed venous saturation can only fall so much. With progressively higher altitudes and falling oxygen tensions, the volume of oxygen that can be extracted from arterial blood becomes progressively limited and an increased cardiac output is required to meet even resting oxygen demand.

The CNS is disproportionately affected by hypoxia. It is the first tissue to malfunction with oxygen deficiency, and the first one to succumb to anoxic conditions. Oxygen consumption by the brain is characterized by its relative consistency; it is at a high level at rest, and does not change significantly in response to states such as exercise. The requirement by the CNS for an unfailing supply of oxygen is perhaps best illustrated by the physiologic lengths to which the organism will go after a traumatic episode, by supplying blood to the brain at the expense of nearly all other tissues.

Relative degrees of hypoxia result in subtle neurologic symptoms. These are amply illustrated in an extract of a report by Captain R. W. Schroeder in which he discussed his aviation altitude record of 29,000 ft (8,800 m) on September 18, 1918 (see Chapter 1):

> At 20,000 feet, while still climbing in large circles, my goggles became frosted, making it very difficult for me to watch my instruments. When I reached 25,000 feet I noticed the sun growing very dim. I could hardly hear my motor run, and I felt very hungry. The trend of my thoughts was that it must be getting late . . . I went on talking to myself, and this I felt was a good sign to begin taking oxygen, so I did. I was then over 25,000 feet, and as soon as I started to inhale the oxygen the sun grew bright again, my motor began to exhaust so loud that it seemed something must be wrong with it. I was no longer hungry and the day seemed to be a most beautiful one . . .
>
> I kept at it until my oxygen gave out, and at that point I noticed my aneroid indicated very nearly 29,000 feet. The thermometer 32° below zero C. and the R.P.M. had dropped from 1600 to 1560. This, considered very good. But the lack of oxygen was affecting me. I was beginning to get cross, and I could not understand why I was only 29,000 feet after climbing for so long a time. I remember that the horizon seemed to be very much out of place, but I felt that I was flying correctly and that I was right and the horizon was wrong.
>
> About this time the motor quit. I was out of gasoline, so I descended in a large spiral. When I had descended to about 20,000 feet I began to feel better . . . I did not see the ground from the time I went up through the clouds above Dayton, Ohio, until I came down through them again at 4000 feet above Canton, Ohio, over 200 miles from where I started (8).

Signs and Symptoms of Hypoxia

The warning symptoms of hypoxia tend to be subtle, and the symptom onset insidious. Recognition of developing hypoxia is also hampered by the fact that the cognitively impaired individual has difficulty recognizing his or her own cognitive impairment; an example is the intoxicated driver who is convinced he is in full control of his vehicle. Therefore, considerable attention should be devoted to acquainting the aviator with the early warning signs of hypoxia.

TABLE 2-4

Effect of Acute Exposure to Altitude on Pulmonary Ventilation

		Altitude in Meters (ft)				
	m	*Sea Level*	*3,700*	*5,500*	*6,700*	*7,600*
Pulmonary Function	*ft*	*Sea Level*	*12,000*	*18,000*	*22,000*	*25,000*
Minute volume (L/min)		8.5	9.7	11.1	15.3	—
Respiratory rate (per minute)		12.0	14.0	12.0	15.0	—
Tidal volume (L)		0.71	0.69	0.92	1.02	—
Alveolar P_{O_2}		103.0	54.3	37.8	32.8	30.4
Alveolar P_{CO_2}		40.0	33.8	30.4	28.4	27.0

Note: The ascent was accomplished at 1400 m/min (4,500 ft/min). The subjects remained at altitude for 30 to 60 minutes.
Minute volume and respiratory rate are average values. The tidal volume was calculated.
(Adapted from Rahn H, Otis AB. Alveolar air during simulated flights to high altitudes. *Am J Physiol* 1947;150:202.)

Signs and symptoms associated with altitude hypoxia are due to either hypoxia itself, or to the associated hypocarbia, or to both. Objective signs include tachypnea, hyperpnea, and cyanosis. Signs of CNS dysfunction, some of which may also be noted as symptoms by the individual, include confusion; behavioral changes such as excitement or belligerence; loss of coordination; and eventually unconsciousness. Symptoms of hypoxia may include dyspnea, headache, lassitude, drowsiness, euphoria, and blurred or tunnel vision. Symptoms due to hypocarbia, such as circumoral or acral paresthesias, commonly accompany hypoxic symptoms and are often the first symptoms noted by the aviator. This is to be expected because the peripheral chemoreceptors will initially try to maintain an arterial oxygen tension near 60 mm Hg by hyperventilation.

Because there is always a risk of equipment failure at altitude, early recognition of hypoxic symptoms is mandatory. Unfortunately, the constellation of hypoxic symptoms and their sequence of appearance tend to be idiosyncratic to the individual. Subjecting the aviator to hypoxia under controlled conditions, such as in a hypobaric chamber, allows the flyer to experience his or her individual symptoms of hypoxia. As a rule, the individual's symptoms do not change dramatically over time, but refresher training in a chamber does reacquaint the individual with the symptoms, as well as identify any change in symptoms.

Effective Performance Time

Below 3,048 m (10,000 ft), few normal individuals notice hypoxic symptoms while at rest, although measurable deficiencies in color and night vision exist. Depending on the individual, scotopic visual function may be reduced by approximately 10% at 1,524 m (5,000 ft), with a 28% reduction at 10,000 ft. From altitudes of 10,000 ft to approximately 15,000 ft, cardiorespiratory compensation will allow the unacclimatized individual to function, typically for an indefinite period of time. Nonetheless, some degree of impairment is the rule with decreased alertness and impaired judgment and coordination. Above approximately 15,000 ft, the unacclimatized individual will usually become severely impaired usually within a matter of minutes or even seconds, depending on the altitude. However, it should be noted that individual tolerances vary markedly. The length of time an individual is able to perform useful flying duties is known as the *effective performance time* (EPT), or time of useful consciousness (TUC). This does not reflect the onset of unconsciousness *per se*—at 18,000 ft, for instance, the individual might not reach such a state—but rather the period of time beyond which the aviator would be unlikely to take corrective or protective action. Typical EPT values for resting individuals are given in Table 2-5.

Note that at higher altitudes, EPT values are considerably shorter than the period of time the average individual could breath-hold. Although at altitude mixed venous oxygen tension falls below its typical resting level of 40 mm Hg, at extreme altitude alveolar oxygen tension will fall lower still, resulting in a net diffusion of oxygen out of the pulmonary capillary. Therefore, EPT at that altitude is a function of circulation time. Exercise of even modest levels shortens the EPT because decreased circulation time and increased peripheral demand result in a faster loss of oxygen.

TABLE 2-5

Effective Performance Time at Altitude

Altitude		
m	*ft*	*Effective Performance Time*
5,500	18,000	20–30 min
6,700	22,000	10 min
7,600	25,000	3–5 min
8,500	28,000	2.5–3 min
9,100	30,000	1–2 min
10,700	35,000	0.5–1 min
12,200	40,000	15–20 s
13,100	43,000	9–12 s
15,200	50,000	9–12 s

Treatment of Hypoxia

With the onset of hypoxia, administration of 100% oxygen is critical. If the aviator was already using an oxygen system when symptoms began, either the concentration should be increased, or a different source of gas should be employed. At altitudes above 12,192 m (40,000 ft), oxygen must be administered under positive pressure. After oxygen administration, breathing rate should be slowed to 12 to 16 breaths/min, because otherwise persistent hypocarbic symptoms might incorrectly persuade the aviator that hypoxia was persisting. Oxygen equipment should be inspected because certain problems (e.g., disconnected hose) can be readily identified and corrected in the aircraft. If an immediately correctable cause cannot be identified, the aviator should if at all feasible descend to below 10,000 ft altitude. Recovery from hypoxia is usually immediate, but symptoms such as fatigue and headache may persist, particularly after prolonged episodes of hypoxia.

On occasion, administration of oxygen to correct hypoxia is followed by an increase in the severity of symptoms, a phenomenon known as *oxygen paradox*. Symptoms typically consist of confusion and worsened vision and even loss of consciousness may occur. This phenomenon is thought to occur because the reoxygenation may be accompanied by a fall in systemic blood pressure, and it seems most likely that the transient hypotension in the face of preexisting cerebral vasoconstriction due to hypocarbia causes cerebral ischemia. The cause of the hypotension itself is unclear. The direct cardiovascular effect of supplying oxygen in a hypoxic state is to reduce pulmonary vascular resistance, but the resulting increase in left ventricular preload and increased cardiac output would not explain systemic hypotension. It seems most likely that the phenomenon is due to transient release of a vasodilator substance such as oxygen radicals or nitric oxide, but the precise mechanism is unknown.

Oxygen Toxicity

Regardless of how vital any substance is to biologic processes, an excess is likely to be toxic, and oxygen is no exception. Aerobic organisms have managed to adapt to atmospheric oxygen tensions while avoiding toxicity, but the margin of safety is small. It should not be surprising that the existing antioxidant defenses are readily overwhelmed because exposure to oxygen at concentrations higher than 21% is largely a man-made phenomenon.

Prolonged exposure to oxygen tensions in excess of 400 mm Hg, or approximately 55% concentration at sea level, risks pulmonary damage. The time to onset of clinical toxicity is considerably shortened at higher partial pressures, with a latency of 1 to 3 days at a P_{IO_2} of 760 mm Hg, and 8 to 10 hours at 1,520 mm Hg. The time to onset of toxicity varies between individuals and species. Toxicity is hastened by certain drugs and by radiation, and may be delayed by prior sublethal oxygen exposure. Such provocative and palliative factors often appear to be paradoxical. For instance, disulfiram protects rats from hyperbaric oxygen toxicity, but potentiates normobaric toxicity. Pre-exposure of the same species to 80% oxygen renders the animal resistant to subsequent 95% oxygen, whereas pre-exposure to 60% oxygen actually increases the subsequent toxicity of 95% oxygen.

It is reasonably clear that toxicity is a function of oxygen partial pressure rather than concentration. Because of the engineering advantages of maintaining a sealed cabin at pressures lower than atmospheric, in the early years of the space program animal and later human research subjects were exposed to 100% oxygen at high altitudes (e.g., 10,200 m; 33,500 ft) for days to weeks. There were isolated reports of possible toxicity, such as instances of retrosternal discomfort that typically cleared with further exposure, and subjects who displayed an asymptomatic increase in pulmonary shunt fraction, but in general the absolute oxygen atmosphere was well tolerated at that altitude. Early astronauts were maintained in a similar atmosphere without evident toxicity, a practice that was abandoned after the disastrous Apollo fire of 1967.

Normal volunteers exposed to absolute oxygen at sea level typically experience substernal discomfort and mild dyspnea beginning 4 to 22 hours after onset of exposure. During this period, the only objective finding is decreased tracheal mucociliary clearance. Longer exposure to 100% oxygen typically results in decreases in vital capacity, pulmonary compliance, and diffusing capacity, with an increase in intrapulmonary shunting. Individual tolerance varies, but few volunteers have tolerated 100% oxygen for longer than 3 days. The longest voluntary exposure reported was 110 hours, but this resulted in severe dyspnea and acute respiratory failure (9).

In most part owing to idiosyncratic tolerances, it is difficult to specify safe limits for oxygen exposure. In general, normal humans appear to tolerate 24 to 48 hours of absolute oxygen at sea level, and oxygen concentrations of less than 50% can be tolerated for extended periods of time with little evidence of tissue injury. Given these findings, the risk of oxygen toxicity in civilian or military aviation appears to be negligible. An exception would have to be made in the case of an individual exposed to potentiating agents. Therapeutic doses of thoracic radiation, as well as certain drugs such as bleomycin, are synergistically toxic with oxygen. It is probable that the pneumonitis which occasionally complicates treatment with either bleomycin or radiation therapy represents potentiation of oxygen toxicity at ambient oxygen levels, due to increased free radical damage. Hyperoxia increases the risk of developing pneumonitis from either treatment. Of greater aeromedical concern is delayed toxicity, occurring when the previously treated individual is subsequently exposed to oxygen. Cases of delayed toxicity, most of them from the surgical literature, have been described months and occasionally even years following initial treatment; although most cases have been described within a year of exposure, this may well be artifactual, because it corresponds to the most likely period for delayed operative intervention in treatment of malignancy. The risk of such toxicity is controversial, because its occurrence is inconsistent, probably due to the multifactorial nature of oxygen toxicity itself. Pertinent aeromedical literature is essentially nonexistent. Although the risk is probably low, it seems wise to restrict those aviators who have received therapeutic doses of bleomycin or thoracic radiation from routine exposure to 100% oxygen.

Neural toxicity from oxygen is not a concern in aerospace operations because such toxicity requires exposure to 100% oxygen at pressures twice that of sea level (2 ATA). It is, however, of concern in hyperbaric treatment of altitude DCS, where absolute oxygen is administered at pressures of up to 2.8 ATA. The major risk is the development of generalized seizures, which may be preceded by muscle twitching and incoordination. Because the great majority of individuals can tolerate up to 30 minutes of 100% oxygen at 2 ATA, treatment regimens generally consist of 20 to 30-minute periods of pure oxygen, separated by 5- to10-minute periods of air breathing. This prolongs the latency of neural oxygen toxicity while allowing satisfactory resolution of DCS.

PROTECTION AGAINST HYPOXIA

The dominant theme of this chapter has concerned the central role of oxygen in the maintenance of aerobic life. Because adaptation to the hypoxic environment of altitude is limited to relatively low elevations, and furthermore is incompatible with the brief exposures typical of aviation, the answer is instead to engineer appropriate systems into the aircraft for hypoxia protection.

The value of the administration of supplemental oxygen as a means of alleviating hypoxia in rarefied atmospheric conditions was elegantly demonstrated by the great French physiologist Paul Bert in experiments he conducted in his hypobaric chamber in the 19th century (see Chapter 1). He used this evidence to advise balloonists about the value of breathing oxygen when flying at altitude. Indeed, it was the failure of three balloonists during high altitude Zenith flights to properly use the stored oxygen they had taken that led to the deaths of two of them during an ascent above 26,200 ft (8,000 m).

Although heavier than air controlled flight began in 1903 with a short flight that attained only very limited altitude, flights of 600 mi were completed by 1913, the air speed record stood at 120 mph and an altitude of 20,000 ft had been reached. Georges Lagagneux, a French pilot, is credited with the first use of supplemental oxygen in an aircraft when he flew to an altitude of 20,014 ft in 1913. By the outbreak of war in Europe in 1914 most major powers had aircraft in military use and urgent efforts to improve performance were occurring. The tactical advantage of height in aerial combat soon became clear and drove the requirement for ascent to ever-higher altitudes. However, the physiological limits of unsupported ascent to altitude became a significant limiting factor in the advancement of air power. This limit was solved by the development of the first practical aircraft oxygen systems. German developments in this field allowed the aircraft and airship crews to achieve greater heights than their allied adversaries. The Dreager company even produced the first liquid oxygen (LOX) system for airborne use. Their designs were soon copied by the Allied Forces to redress this military advantage. Research conducted by the Royal Flying Corps demonstrated beyond a doubt the value of providing oxygen in flight, which resulted in efforts to make such systems easier for the aircrew to operate. This drove the change in delivery systems from a mouthpiece (commonly termed a *pipe-stem*) to a face mask molded to fit with a seal at its edge. The development of methods that economized the use of oxygen, through the use of a reservoir rather than simple continuous flow and eventually through systems that delivered oxygen on demand, improved capabilities still further.

Through the interwar years, developments continued at a slower pace but by the outbreak of the World War II aircrew oxygen systems were in routine use. Shortly after the end of World War I in the United Kingdom, J.S. Haldane was able to show that with the use of supplemental oxygen the alveolar partial pressure of oxygen could be maintained at acceptable levels, and that by breathing pure oxygen, hypoxia could be avoided up to 35,000 ft. Over 40,000 ft, however, he recommended that the individual be offered an alternative form of protection. This was the use of a pressurized suit, similar in some ways to a diving suit, filled with oxygen and maintained at a pressure of at least 130 mm Hg. This technique effectively removed the physiological limitation to ascent. By 1933 such a suit was developed and an American balloonist, Mark Ridge, was safely exposed to an altitude of 84,000 ft in a decompression chamber. In 1934 Wiley Post, the famous pioneering aviator, flew his aircraft, Winnie May, to an altitude of 40,000 ft wearing a similar suit (see Chapter 1).

It had been recognized for some time that an alternative solution to protect a pilot from the dangers of hypoxia would be to pressurize the cockpit. In 1931, a pressurized balloon gondola was used to allow Auguste Picard to attain an altitude of 51,795 ft. The first successful pressurized aircraft, the Lockheed XC-35, flew in 1935 but throughout World War II pressurized aircraft remained relatively rare, although a notable exception was the B-29 Superfortress. Since the end of World War II, however, cabin pressurization has become a standard feature of both combat and commercial aircraft, although the degree of pressurization commonly differs. Nonetheless, in the 50 years after the Wright Flyer 1 took to the air, the principal developments of personal oxygen systems, pressure suits, and cabin pressurization had all occurred. The remainder of this chapter will discuss the modern use of such systems.

Cabin Pressurization

Aircraft

Unpressurized aircraft are limited in altitude to avoid exposing crew and passengers to an unacceptable degree of hypoxia. National regulatory bodies apply limitations on the permissible service ceiling of each aircraft type. Commonly, aircraft with no pressurization capability are allowed to operate at altitudes no greater than 10 to 12,000 ft. This altitude limit may be lowered at night to take into account of the effect of low-grade hypoxia on night vision. The altitude to which pressurized aircraft may fly is regulated so that crew and, where appropriate, passengers will have an adequate oxygen supply available for use in the event of loss of cabin pressure. Commercial aircraft pressurization can provide a "shirt sleeve" environment within the cabin with an equivalent altitude no greater than 8,000 ft while the aircraft can operate up to approximately 40,000 ft. Commonly, military combat aircraft are pressurized to a lower degree than commercial or noncombat aircraft because they are more likely to sustain damage that may result in loss of pressurization. Such a system reduces the risk of DCS and reduces the utilization of oxygen, but makes it necessary for the crew to wear a personal oxygen system throughout flight.

Cabin pressurization systems are designed to pass compressed air into the cabin or cockpit and to control its outlet so as to raise the pressure within the cabin. A differential pressure is therefore established between the inside and the outside of the aircraft. The controlled entry and exit of air through the cabin ensures a supply of fresh air and is integrated into the cabin environmental control system to regulate the cabin temperature. Modern commercial aircraft commonly recirculate 50% of cabin air through high-efficiency particulate (HEPA) filters. This increases fuel efficiency without compromising cabin air quality although the latter has been a matter of some controversy.

Commercial aircraft are generally pressurized on ascent from ground level (Figure 2-8). The maximum pressure differential across the fuselage is on the order of 8.5 to 9 lb/in^2 and is termed a *high- differential pressurization system*. Once that differential has been reached, further ascent of the aircraft will lead to a further increase in cabin altitude and, given the requirement to maintain cabin altitude at or below 8,000 ft, a maximum acceptable aircraft altitude can be derived. A military combat aircraft may not pressurize at all until it has ascended to 8,000 ft but then holds the cockpit pressure at that altitude (termed *isobaric*) until its

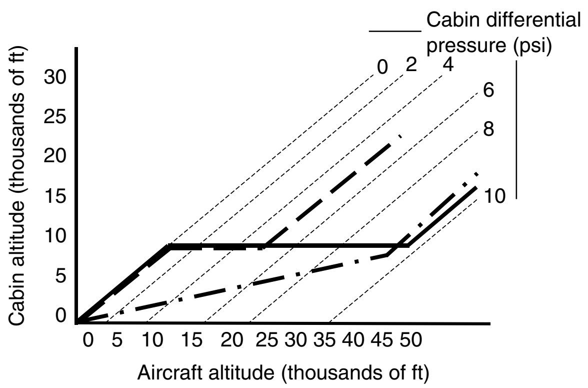


FIGURE 2-8 Graphs of the relationship between aircraft altitude and cabin altitude in a commercial transport aircraft (— ·), a high-differential military aircraft (—), and a low-differential military aircraft (— —). The pressurization of a commercial aircraft begins at ground level and cabin altitude rises more slowly than aircraft altitude until the maximum cabin differential pressure is reached. In military aircraft, the cabin is typically not pressurized until an altitude of 8,000 ft is reached. Thereafter an isobaric cabin altitude is held until the maximum cabin differential is reached. Further aircraft ascent will cause cabin altitude to rise again.

maximum pressure differential has been reached. In these aircraft this differential may be between 3.5 and 5.25 lb/in^2 in high-performance aircraft, whereas high-differential military aircraft may reach a maximum differential pressure of 9.2 lb/in^2. Other pressurization schedules have been used, including an enhanced high differential one in supersonic transport aircraft.

Spacecraft

At the altitudes of orbit for manned spacecraft the atmospheric pressure is so low that the compression of the relatively few molecules of air present is insufficient to provide a usable gaseous atmosphere inside the craft. Therefore, spacecraft must be pressurized by using systems that maintain the cabin environment without exchange of gases with the environment. Russian spacecraft have been designed from the early stages of their space program to provide a cabin environment pressurized to 1 atmosphere (sea-level equivalent) and composed of gas with a similar proportion of oxygen (21%) to air. This imposes challenges in terms of capsule strength and weight. Early U.S. spacecraft (Mercury and Gemini) had lower cabin pressures, thereby reducing weight, but had a high oxygen content to avoid hypoxia, giving rise to a greater risk of capsule fire. The accident and fire that killed three NASA Apollo astronauts led to a modification of this policy and design of the system in the Space Transportation System (STS). In the STS, the Orbiter is pressurized to a sea-level equivalent throughout much of the flight, but can be depressurized from 14.7 lb/in^2 to approximately 10 lb/in^2 in preparation for extravehicular activity.

Provision of Oxygen

Irrespective of the presence of a cabin pressurization system, the requirement for the provision of oxygen to the occupants of an aircraft is related to the ambient pressure to which they are exposed. The design of the system may also have to accommodate the need for physiological protection against hypoxia following a loss of cabin pressure, resulting in a sudden exposure to a much higher altitude. Such systems have to be designed to protect against hypoxia in an emergency in which the user is exposed to the ambient pressure at which the aircraft is flying (or even higher due to the effect of aerodynamic suction). The following pages will describe the requirements for oxygen systems pertinent to the challenges faced by the users, and therefore the altitudes and environmental pressures given refer to the conditions surrounding the occupants of the aircraft, rather than the aircraft itself.

Classes of Oxygen Systems

Closed Circuit Oxygen Systems

In closed circuit oxygen systems, advantage is taken of the relatively small proportion of the inspired air at sea level that is required to meet metabolic requirements. For example at sea level, 16% of the expired gas is oxygen. Therefore only approximately a quarter of the inspired oxygen is used and the rest exhaled. Therefore, recycling expired gas can economize on the amount of oxygen required to be delivered by an oxygen system.

However, this advantage diminishes with altitude because there are technical difficulties in ensuring that the correct amount of oxygen is delivered into the closed system to replenish the oxygen consumed. Furthermore, the gas in a closed system contains (a) expired water vapor that can condense and freeze at low temperatures, (b) an increasing concentration of carbon dioxide which must be removed from the circuit, and (c) a rising proportion of nitrogen, if there is any inward leakage of air. Therefore, such systems tend to be complicated by the need to address these aspects.

Closed circuit oxygen systems are used in space flight, and in some underwater breathing systems, but rarely in aviation, although some smoke hoods used by cabin crew during an on-board fire are based on oxygen systems of this type.

Open Circuit Oxygen Systems

In open circuit systems the expired gas is vented to the environment. Although this is relatively wasteful with regard to oxygen utilization, it has the considerable advantage of simplicity. The delivery of oxygen to the user may be continuous throughout the respiratory cycle or on demand, that is when an inspiratory effort initiates the flow of oxygen. The characteristics of such systems and the general and physiological design requirements are described in the subsequent text.

General Requirements of Oxygen Systems

Convenience

To the degree possible, a system should impose the minimum burden on the user and should be as automatic as possible.

The user should merely have to don the equipment (usually a mask) and connect to the system with ease.

Evaluation of Integrity

Having donned the system, the users should be able to assure themselves that it is functioning correctly and any failure should be immediately apparent. This requirement also include an indication of flow and, where appropriate, an indication of the oxygen contents held in storage. The latter is usually achieved with a pressure gauge visible to the user. Flow indication is commonly achieved with some form of "blinking" flow sensor. These sensors blink when flow occurs; a constant indication, with or without flow, indicates a fault in the system.

Safety Pressure

The primary aim of an oxygen system is to protect against hypoxia by the provision of an amount of oxygen sufficient to maintain adequate alveolar partial pressure. Inward leakage of ambient air may compromise this objective and is best prevented by a small overpressure of the system (safety pressure). This overpressure may be controlled so as to only be present when a significant altitude is reached, typically 12,000 to 15,000 ft in U.K. military oxygen systems and higher (>20,000 ft) in U.S. systems. In a similar manner, safety pressure can be used to protect the user from inhaling smoke or toxic fumes in the cockpit. In these cases no dilution of the inspired gas is acceptable so it must be possible to select the delivery of 100% oxygen and avoid the mixing of oxygen with cabin air. This capability can also be used to reduce the risk of DCS by "prebreathing" oxygen to reduce the nitrogen stored in the body.

Temperature

The inspired gas should be at a temperature that will be tolerable to the user. An inspired gas temperature within $\pm 5^{\circ}$C of the cockpit temperature is generally acceptable. The system itself should be resistant to the effects of temperature. In particular, exposure to low temperatures should not cause freezing of water vapor within the unit, which could prevent normal operation.

Duplication

Where a personal oxygen system is used as the primary means of protection against hypoxia, such as in a military combat aircraft, a degree of redundancy is essential in the delivery of oxygen. Simple continuous flow systems were utilized as a form of backup to the breathing regulator but have been mostly superseded by the provision of a secondary regulator with most of the features of the primary one. This allows for economical use of breathing gas and therefore has implications for mission effectiveness as well as crew safety. A form of redundancy is also required for the potential failure of the main oxygen supply system, be it stored oxygen or oxygen generation, and in ejection seat-equipped aircraft this function can be combined with the provision of post–ejection protection against hypoxia with a seat-mounted gas store.

Underwater Escape

A ditched aircraft will sink rapidly. Therefore, oxygen equipment can be designed to operate to a modest depth for a short time. In some air forces a short-term air supply is provided to assist escape from a helicopter underwater.

Physiological Requirements of Oxygen Systems

Oxygen Concentration

As ambient pressure reduces on ascent the partial pressure of respired gases, including oxygen, within the lungs will fall in parallel unless the proportion of a gas within the inspired air is raised. The amount by which the inspired oxygen concentration must be raised to maintain an alveolar partial pressure equivalent to breathing air at sea level can be calculated.

Figure 2-9 shows the concentration of oxygen required to be present in the inspired gas to maintain the P_{AO_2} at 103 mm Hg during ascent from ground level to an altitude of 34,000 ft. For example, raising the fractional inspired oxygen content from 21% to 63% at 25,000 ft will maintain a P_{AO_2} of 103 mm Hg. Although healthy individuals may tolerate some reduction in alveolar P_{O_2}, some reduction in memory and learning ability, as well as reduction in night vision, are known to occur when breathing air at an altitude of 8,000 ft. Furthermore, if a lower fractional increase in inspired oxygen were used, any inward leakage through a face mask that resulted in the in-drawing of ambient air would be even more hazardous because there would be a reduced margin of safety with respect to protection against hypoxia.

However, some compromise of the minimum acceptable oxygen partial pressure can be tolerated when a loss of cabin pressure occurs at high altitude. In this circumstance, and when positive pressure breathing is used to provide short duration protection against hypoxia, a P_{AO_2} of 30 mm Hg may be acceptable for a very limited duration, provided it rises rapidly to at least 75 mm Hg among aircrew while the aircraft descends.

A very basic oxygen system could provide 100% oxygen at all altitudes. This could have a number of advantages

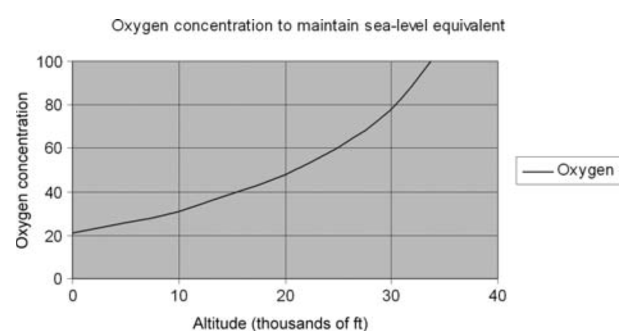


FIGURE 2-9 Graph of the concentration of oxygen required to be present in the inspired gas to maintain the P_{AO_2} at 103 mm Hg during ascent from ground level to an altitude of 34,000 ft.

including cost and mechanical simplicity. However, such a system has a number of significant disadvantages:

1. It is wasteful of oxygen at low altitudes because 100% oxygen is only required when altitudes in excess of 33,000 ft are reached.
2. Long periods of breathing 100% oxygen at altitudes below 18,000 ft can give rise to retrosternal discomfort.
3. Breathing high inspired oxygen concentrations will enter the middle ear cavity and its subsequent absorption can give rise to ear discomfort and deafness (delayed otic barotraumas), a process that is reduced by the presence of nitrogen in the inspired gas.
4. During increased acceleration, breathing 100% oxygen has been associated with the collapse of basal segments of the lung (acceleration atelectasis), giving rise to cough, dyspnea, and chest pain. The symptoms are aggravated by the use of anti-G trousers but are prevented by the presence of at least 40% nitrogen in the inspired gas.

In summary, an aircraft oxygen system should deliver a concentration of oxygen sufficient, but not greatly more than that required, to prevent hypoxia and ideally it should provide an inspired gas composition that will result in an alveolar P_{O_2} equivalent to breathing air at sea level. At very high altitudes (above 40,000 ft), the need for positive pressure breathing with 100% oxygen [pressure breathing for altitude (PBA)] to achieve an acceptable P_{AO_2} can give rise to compromise between the degree of pressure breathing required and the severity of hypoxia suffered for a short period before descent results in an improvement in the P_{AO_2}.

Pulmonary Ventilation

If an oxygen system is incapable of meeting the ventilatory demands of the user in terms of minute ventilation and instantaneous flow, the unmet ventilatory needs may be subjectively unpleasant and can give rise to significant disturbances of respiratory patterns. Respiratory measurements made during high-performance flights reveal that ventilatory demands can be very high, especially in air combat, and even when the pilot initially runs to his aircraft. Aircrew oxygen system should therefore provide a minute ventilation of 50 L/min [ambient temperature and pressure dry (ATPD)], and peak inspiratory flows of up to at least 200 L/min (ATPD). Standards to specify these performance criteria in aircrew oxygen systems in military aircraft have been defined by NATO and in AeroSpace Interoperability Command [formerly Air Standardization Coordinating Committee (ASCC)] Air Standards (3).

Resistance to Breathing

Most oxygen systems impose some additional flow resistance but this must be minimized or unacceptable physiological side effects may occur. The precise effects an individual experiences when confronted with subjectively persistent resistance to breathing are variable, with many individuals overbreathing (hyperventilating), whereas some try to moderate and reduce their demands so as to avoid the unpleasant sensation. Neither of these effects is desirable. Such respiratory resistance may be so uncomfortable as to make the user have sensations of impending asphyxia and compel them to discard their breathing system despite the risk of hypoxia. To reduce the risk to the aircrew from an inadequately designed oxygen system, there are Air Standards that define acceptable levels of mask cavity pressure at various flow rates.

Added Dead Space

In addition to the normal anatomic dead space, an oxygen system imposes a further functional dead space. To avoid significant rebreathing of expired carbon dioxide, the dead space in the mask should be kept to a minimum and ideally be less than 150 mL. In the event of a rapid decompression, gas trapped in the dead space of the oxygen system will contain an oxygen concentration inappropriate for the altitude to which the user of the system is now exposed. Therefore, it is critically important that this gas be replaced as quickly as possible by gas with an oxygen content high enough to prevent hypoxia. This is only possible if the gas trapped in the dead space is removed immediately and a breathing gas with the correct composition of oxygen to prevent hypoxia is supplied within one breathing cycle.

Airborne Oxygen Supplies

Gaseous Oxygen

The most common form of oxygen storage used in aircraft is a pressurized gaseous oxygen cylinder. Many cylinders have an operating maximum pressure of 1,800 lb/in^2, are made of steel, and are sometimes wire-bound in military aircraft to reduce the risk of release of shrapnel if shattered in combat. Cylinders with an even higher pressure, up to 3,600 lb/in^2, are sometimes used in commercial and some military aircraft. This has the benefit of reducing the space required to carry a large quantity of oxygen but can increase the logistic challenge of supporting such systems.

Gaseous oxygen is widely available although aviators' oxygen has to meet certain quality requirements, such as dryness, that are more stringent than therapeutic oxygen. For example, gaseous oxygen used in aviation must be 99.5% O_2 by volume and contain no more than 0.02 mg of water/L of gas at sea level. This is considerably more pure and dry than therapeutic oxygen used in hospitals. However, condensation and subsequent freezing of water vapor in the oxygen storage system could have disastrous consequences in flight as discussed earlier.

Aircraft cylinders can be charged until the pressure within it reaches its operating maximum. As it is used, the pressure in the cylinder will fall, although it is prudent to avoid complete discharge of the cylinder to prevent ingress of moisture.

The amount of oxygen held in aircraft cylinders will depend on the aircraft type and endurance. However, oxygen cylinders are relatively bulky and heavy. Whereas little or no stored oxygen may be acceptable in some types of aircraft, training aircraft and those in which the oxygen system is not routinely used throughout flight, it is unacceptable in combat aircraft. Small cylinders of gaseous oxygen are commonly available on commercial aircraft for the in-flight treatment of passengers and as the emergency oxygen supply fitted to the ejections seats of combat aircraft.

Liquid Oxygen Storage

One liter of LOX can yield 840 L [normal temperature and pressure (NTP)] of gaseous oxygen. For this reason, it is the commonly used form of stored oxygen in combat aircraft because this economy of size and weight is critical in this type of aircraft. Moreover, LOX can be held in a relatively low-pressure vessel, but to be liquefied it has to be cooled to a temperature of −183°C at 1 atmosphere pressure.

Much LOX is wasted during production through vaporization and charging of vessels. Moreover, LOX is a hazardous substance to handle and there have been a number of serious fires in production plants, including shipboard ones.

Charging and using LOX vessel is a three-phase operation involving (a) the filling phase in which the vessel is exposed to LOX that initially evaporates and thereby cools the vessel sufficiently to retain oxygen in the liquid state, (b) the build-up phase in which liquid pressure rises in the vessel to approximately 70 to 115 lb/in^2, and finally (c) a delivery phase in which breathable oxygen can be derived from the vessel. The avoidance of thermal stratification within the LOX, which could lead to a loss of normal operating pressure when colder liquid is disturbed within the vessel, requires an additional process to be carried out that has the effect of warming the liquid contents to a consistent temperature. As it is used, the pressure within the vessel falls and more LOX vaporizes. Gaseous oxygen is channeled to the aircrew through a supply system that allows the gas to warm to an acceptable temperature before it is inspired.

In addition to the hazards of LOX production, there are hazards associated with the use of LOX because it can become contaminated by toxic materials, especially hydrocarbons, and these may accumulate so that a bolus of contamination may be released in a relatively high concentration to the user. The complexity and logistic requirements of LOX production and use are substantial. Therefore, LOX systems are now being superseded in combat aircraft by on-board oxygen production.

On-Board Oxygen Generation Systems

The generation of oxygen as a product of a chemical reaction can be used to produce breathable oxygen rapidly. Most chemical generators are designed to produce oxygen when sodium or potassium perchlorate reacts with iron. For example:

$$NaClO_3 + Fe = FeO + NaCl + O_2$$

Such reactions are exothermic and once initiated by raising the temperature of the reactants to more than 250°C, will usually proceed to exhaustion, with the coincidental release of significant amounts of additional heat. The active chemicals are usually formed with a binder into a cylindrical "candle." The initial heat source is generated within an iron-enriched zone which itself is activated by either percussion or an electrical heating wire.

Some solid candles have been used to provide oxygen in manned space activities, in particular on the Russian space laboratory Mir, and as a backup oxygen system on the International Space Station. In aviation, they are often used as a convenient means of providing emergency oxygen for passengers in commercial aircraft although incorrect storage of these units in transit has been associated with the loss of an aircraft. They have also been developed by some manufacturers as an alternative to seat mounted emergency oxygen in combat aircraft.

Chemical generation of oxygen by other means is also possible. For example, potassium superoxide reacting with water liberates oxygen during the formation of potassium hydroxide. This technique has been used in self-contained breathing escape devices and provides a further advantage in that the potassium hydroxide reacts with expired carbon dioxide, thereby reducing its accumulation within this closed system.

Concentrating oxygen from air has considerable logistic and operational advantages for airborne use. Pressure swing adsorption through a molecular sieve oxygen concentrator (MSOC) has now become practical, and such systems are being installed in most modern combat aircraft. The system is based on the supply of compressed air to a bed in which nitrogen is retarded within the matrix structure of the sieve material. This adsorption process does not result in the chemical combination of nitrogen with the sieve material, usually zeolite, but is dependent on the availability of adsorption sites within the bed and these will eventually be filled. However, when the bed is depressurized the nitrogen molecules are released and can be flushed from the bed.

Zeolites are aluminosilicates with a crystalline structure of SiO_4 and AlO_4 arranged tetrahedrally. The cavities within the tetrahedral structure are usually filled by water molecules but when heated these are driven off, leaving an open matrix within which molecules of an appropriate size can be held. Nitrogen is of such a size, but oxygen (and argon) molecules are too large.

The most basic form of the MSOC is therefore based on two beds pressurized in turn and then purged during their depressurized phase. A small proportion of the product gas from the active bed is used to flush the nitrogen from the resting bed. Once flushed the rested bed is again able to adsorb nitrogen when pressurized at the next cycle. By this means an effectively near continuous supply of product gas containing a high concentration of oxygen can be produced. The presence of a plenum in which product gas is held before use removes the potential problem of a respiratory demand being made at the point of change over between one bed and the other. MSOCs in which there are more than two beds can also alleviate this problem as well as assisting the control of product gas oxygen concentration (Figure 2-10).

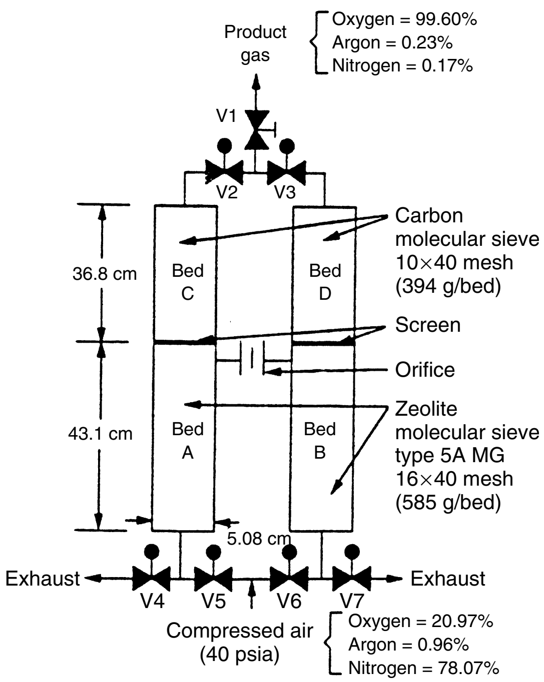


FIGURE 2-10 Two-stage molecular sieve oxygen-generating system. (From Advisory Group for Aerospace Research and Development (AGARD). *Advanced oxygen systems for aircraft.* AGARD-AG-286. Quebec, Canada: NATO Canada Communications Group, 1996:1–95.)

Because neither argon nor oxygen is adsorbed in the bed material, both are present in the product gas in elevated concentrations. This means that the maximum oxygen concentration delivered by an MSOC is approximately 94%, although this value can diminish over time as other factors, such as water contamination of the beds, may adversely affect the maximum achievable concentration. This problem is avoided in many aircraft by switching the breathing gas source to a backup system, which delivers 100% oxygen at high cabin altitudes or in the event of a loss of MSOC supply. In ejection seat–equipped aircraft, this backup oxygen system can be seat mounted to also provide postescape protection against hypoxia.

Aircraft MSOC systems have been designed so that compressed air is derived from the compressor stages of the jet engines. A separate compressor is not required to provide compressed air to the MSOC. However, engine failure does give rise to loss of the main oxygen system and, until an engine relight is achieved, the backup store of oxygen must be used. Despite this drawback, MSOC systems are now used successfully in military combat aircraft, including single-engine ones in which this disadvantage is most apparent.

In routine flight, the maximum oxygen concentration that could be provided from an MSOC is generally not required, and indeed too high an oxygen concentration has significant disadvantages in terms of acceleration atelectasis and delayed otic barotrauma (oxygen ear). Therefore, throughout flight the oxygen concentration should be controlled so as to be high enough to prevent hypoxia, also ensuring that the inspired oxygen concentration being breathed is sufficient for survival in the event of a rapid decompression, but not be so high as to induce the disadvantages described. The actual concentration of oxygen in the product gas can be influenced by a number of factors, including flow across the beds and the interval between their pressurization, known as *bed-cycle time*. Both of these factors can be employed in a feedback system in which the product gas oxygen concentration (or partial pressure) is measured and used to alter the operation of the MSOC, so as to maintain the appropriate oxygen concentration in the product gas within defined limits (Figure 2-11).

FIGURE 2-11 Photograph of molecular sieve oxygen concentrator (MSOC). (Courtesy of Honeywell Aerospace UK.)

In addition to the use of MSOC systems as the main source of breathing gas in a military aircraft, this technique has also been used to provide therapeutic oxygen for respiratory patients traveling by air and is being investigated for use in large commercial aircraft as the means of providing emergency oxygen for passengers.

Oxygen Delivery Systems

Continuous Flow

The simplest form of delivery system is a continuous flow of oxygen from the storage vessel to the user. Usage is calculated easily and the whole apparatus is inexpensive to manufacture. However, a predefined flow has considerable disadvantages. In particular, the delivery of oxygen is not matched to requirements. Inspiration only occupies approximately one third of the normal respiratory cycle, and therefore during the rest of the cycle, the flow of oxygen is wasted. Also, there may be insufficient oxygen to protect against hypoxia, either at altitude or when ventilatory demand is high. If a high flow is provided to alleviate these problems, much of the oxygen will be wasted at low altitude or during quiet breathing.

Such problems can be partially addressed by the use of a range of metering orifices to regulate the flow of oxygen from a storage bottle. Progressive increases in the cross-sectional area of the orifice will allow greater flow to occur. Although this technique allows some form of variability, it remains only a partial solution to compensate for increased altitude and does not compensate for variations in ventilatory requirements.

Incorporation of a reservoir bag between the flow regulator and mask allows oxygen to flow throughout the respiratory cycle and then a bolus of oxygen may be breathed during inspiration. This can reduce oxygen usage by more than 50% and the system may be enhanced further by using a bag which is in direct communication with the mask. If the gas available in the reservoir bag and that flowing from the regulator are insufficient to meet ventilatory demand, ambient air can be drawn in through a port in the mask. Exhaled gas in the respiratory dead space, which has not taken part in respiration and which has a high oxygen and low carbon dioxide content, is passed into the rebreathing reservoir and mixed with the continuous oxygen flow from the system. Such devices are very useful, for example in the provision of therapeutic oxygen to a sick passenger, but they are very vulnerable to the effects of freezing. Also, these systems are incapable of meeting the more sophisticated requirements of aircrew oxygen systems, for which demand flow delivery systems are necessary.

Demand Flow Delivery Systems

Within demand flow systems, it is possible to provide a volume of gas appropriate to meet the ventilatory demands of the user and a gas mixture in which the proportion of oxygen is appropriate for the altitude. This technique ensures protection against hypoxia without undue waste of oxygen, or oversupply leading to delayed otic barotrauma and in high-performance aircraft acceleration atelectasis.

As these systems respond to demand, a wide range of ventilatory requirements can be achieved, ideally up to 300 L/min instantaneous flow, and both safety pressure and pressure breathing can be provided. The altitudes at which safety pressure and positive PBA protection are delivered vary according to national standards. In the United States, safety pressure is generally provided from approximately 20,000 ft, and in the United Kingdom safety pressure is usually delivered when cabin altitude exceeds 12,000 to 15,000 ft. Positive pressure breathing is essential when exposed to altitude above 40,000 ft, where the alveolar partial pressure of oxygen falls below that seen at 10,000 ft breathing air, but some U.S. regulators initiate PBA at a lower altitude to maintain a sea-level equivalent alveolar partial pressure of oxygen. A demand regulator supplied with breathing gas from an MSOC has no requirement to conserve stored oxygen, so safety pressure may be provided from ground level.

Although these design requirements are common to most demand regulators the precise form of the regulator varies. Perhaps the most common is a panel-mounted unit, such as the crew regulator unit (CRU) series of regulators. These provide all the controls the pilot needs to access and display contents (as pressure) as well as an indication of flow (Figure 2-12). Similar panel-mounted units are in service in military aircraft around the world, although in the United Kingdom these were superseded by first man-mounted miniature regulators (similar to those used by the U.S. Navy) and more recently by ejection seat–mounted ones. Even smaller regulators have been used as mask-mounted units, although the disadvantages in terms of weight and movement have resulted in them being used mainly for emergency oxygen in transport aircraft. For aircraft in which aircrew use the breathing system throughout flight and during high-altitude escape, mounting the regulator on the ejection seat reduces the number of regulators required in an aircraft fleet and reduces the risk of damage associated with man-mounted units.

FIGURE 2-12 T-38N pressure-demand regulator.

Air dilution demand regulators contain an aneroid that controls the degree to which ambient air is mixed with oxygen from the storage source. This is achieved by various means, either by suction dilution or injector dilution, but the end result is a system that is responsive to the physiological demands of the individual at the altitude it is operated. Loading of controls within the regulator can be used to induce the provision of safety pressure and PBA at appropriate altitudes.

The introduction of pressure breathing for G protection (PBG) has resulted in further modification of demand regulators so that a G-induced signal, pneumatic or electronic, will cause the regulator to deliver breathing gas at an elevated pressure, proportional to the acceleration to which the pilot is being exposed. The source of additional breathing gas pressure is the oxygen supply and therefore the F_{IO_2} is commonly raised during PBG. New electronic regulators have been developed which may result in increased reliability in service, but the need to ensure aircrew safety and mission completion suggests that a duplex (i.e., a main and stand-by) regulator will remain. In the most modern systems the breathing regulator and the anti-G valve may be combined in the same, seat-mounted unit (Figure 2-13).

Mask and Hose

The final link to the user is the hose and oxygen mask leading from the regulator to the face. The hose routing is related to the location of the regulator and, in ejection seat–equipped aircraft, must be designed to take account of escape requirements. There is considerable advantage in having a single point of connection between the aircrew and the ejection

FIGURE 2-13 Combination anti-G valve and breathing regulator. (Courtesy of Carleton Life Support Systems.)

seat through which oxygen supply, anti-G trouser air, and communications pass. This reduces the number of separate connections to be made while strapping in, speeds emergency ground egress, and simplifies ejection seat sequencing.

Irrespective of the route to the mask, this final conduit of breathing gas is at low pressure but must meet wide respiratory demands. Therefore, the hose should be wide-bore and of low resistance. Movement of the hose should not induce significant fluctuations in gas pressure, and the passage of gas through it should not cause undue noise that would interfere with the use of the mask-mounted microphone (Figure 2-14).

Masks for aircrew that use oxygen throughout flight must fulfil a significant number of functions, fit adequately to prevent leakage, and be comfortable to wear throughout flight. In addition to being the final link in the oxygen system supply chain, these masks also support communication, protect the face in event of bird strike or ejection, and should not obscure vision or impede movement.

Masks worn by aircrew only in an emergency have somewhat easier criteria to meet, although the masks must still protect against hypoxia, including post decompression hypoxia, and not impede the aircrew. Emergency masks designed for passengers have somewhat different criteria. There is no way to ensure that the mask will fit the user, therefore it is designed to fit as wide a range of individuals as possible. The degree of acceptable hypoxia for passengers is greater so indrawing of ambient air is less significant; indeed it is necessary to meet ventilatory demand. The requirements for communication and facial protection are also absent, but the mask must be easy to fit by the untrained and unskilled (despite preflight briefs given in all commercial aircraft.) (Figure 2-15).

Pressure Suits

Full Pressure Suits

When encased in a full pressure suit, the user is exposed only to its internal pressure environment. Therefore, inflation of the suit to an acceptable pressure can provide protection against hypoxia, DCS, and ebullism (the evolution of water vapor from tissue water at altitudes above 63,000 ft). However, a suit inflated to a pressure adequate to allow the wearer to breathe air, that is, a pressure equivalent to 10,000 ft (523 mm Hg) is impractical because it would be impossible to move. Therefore, the inflation pressure is set so as to protect against extreme altitude, but the user must breathe 100% oxygen to ensure normoxia. The underlying principles of pressure suit design used in aviation and space flight are identical, although the practical implication of the differing usage influences design.

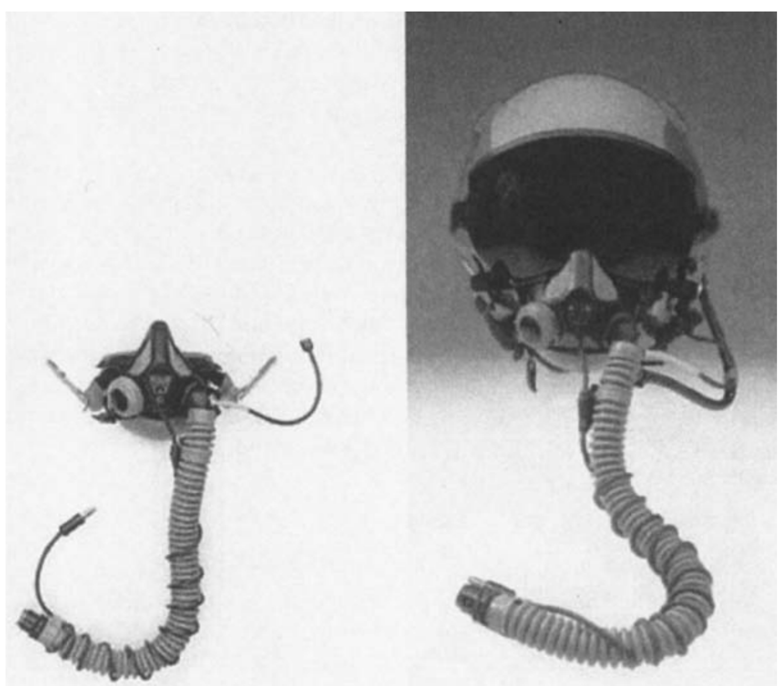


FIGURE 2-14 MBU-2X oxygen mask and connection to the aviator's helmet.

FIGURE 2-15 Passenger oxygen mask. (Courtesy of B/E Aerospace.)

Provided the absolute pressure within the suit is at least 141 mm Hg, and 100% oxygen is delivered to the respiratory tract, severe hypoxia will be prevented. However, to protect against DCS the absolute pressure within the suit should be at least 282 mm Hg, equivalent to an altitude of no higher than 25,000 ft. Some compromise can be reached so that a suit pressure of 226 mm Hg (0.3 bar, 4.3 lb/in^2), equivalent to an altitude of 30,000 ft, makes movement easier while wearing the inflated suit and, provided duration of use is relatively limited, such a pressure can be tolerated without undue difficulties.

The ability to perform extravehicular activity in the near vacuum of space requires a suit pressure of 226 mm Hg (0.3 bar, 4.3 lb/in^2) that is preceded by a period of 4 hours of breathing 100% oxygen, or a reduction in cabin pressure followed by a shorter period of 100% oxygen prebreathing (see Chapters 10 and 28). This prebreathing, or denitrogenation, removes nitrogen from the body stores thereby reducing the incidence and severity of DCS. If a higher suit pressure is available, a shorter period of denitrogenation is needed. Russian space suits have commonly been inflated to higher suit pressures, even up to 420 mm Hg (0.56 bar), although normal operating pressure is 0.4 bar or 5.88 lb/in^2.

Full pressure suits consist of a pressure garment that is impermeable to the gas which inflates the suit. This is contained within a retaining layer that prevents overexpansion on inflation. The outermost layer is a form of fabric that protects the functional elements within. Making a garment with the mechanical strength to withstand the pressure to which it is inflated is particularly difficult around joints, hands, and fingers. Nevertheless, the design of these garments has improved considerably throughout the manned space program, allowing astronauts to conduct complex physical actions while wearing a pressure suit.

Aviators need only wear pressure suits when the risk of decompression at very high altitudes exists. This is generally confined to a few high-flying reconnaissance and research aircraft. Even in the presence of an intact pressurized cabin, partial inflation of a pressure suit can provide a significant measure of protection against DCS during long, high-altitude flights.

In both aviation and space exploration, the thermal comfort of the wearer is important. A high ventilation airflow can conduct some heat away from the body. In aircraft, this can be taken from the engine compressors but a flow of oxygen to the pressure helmet is required to provide a breathing gas that allows adequate protection against hypoxia. Therefore the aircraft suit has two separate compartments. One protects against hypoxia and the other provides pressurization and thermal conditioning. It is necessary to keep the pressure difference between these two compartments as small as possible, but the pressure in the helmet must never be less than the suit body or air would be drawn into the face piece or helmet and hypoxia could ensue. Space suits are liquid cooled and have a one-compartment design.

Partial Pressure Suits

Although full pressure suits provide protection against hypoxia, DCS, and ebullism, they are expensive, complicated, and cumbersome. An alternative system that can be used to make positive pressure breathing tolerable for limited periods is based on providing a partial pressure garment assembly. Commonly this consists of a close-fitting oronasal mask that can deliver oxygen to the wearer at pressures considerably above ambient. The adverse physiological effects of positive pressure breathing include distension of the chest, reversal of the normal breathing cycle, fatigue, and circulatory disturbances leading to syncope. The application of counter-pressure over the chest can alleviate the overdistension of the chest and reduce the fatigue associated with pressure breathing. Inflation of counter-pressure garments over the limbs and abdomen reduce the circulatory disturbances too. Although this method provides no protection against DCS or ebullism it can make pressure breathing at mask pressure more than 30 mm Hg above ambient tolerable for limited periods. Therefore, this can provide short-duration protection following a loss of cabin pressurization at altitudes in excess of 50,000 ft. Immediate descent must be initiated because the degree of protection against hypoxia is limited and DCS may occur following a relatively brief exposure to such altitudes. Such systems provide very little protection against ebullism if the decompression occurs above 63,000 ft.

Lower body and lower limb counter-pressure can be provided by means of inflation of anti-G trousers. These are not being used to protect against acceleration but as an element of the high-altitude partial pressure assembly. Upper limb counter-pressure can also be used to give further circulatory support but this form of assembly is less convenient and rarely used in practice.

Advanced Life Support Systems

The advanced Life Support Systems (LSS) developed for the latest generation of combat aircraft are commonly based on an MSOC oxygen generator, with an ejection seat–mounted emergency backup oxygen store. The pilot may wear a partial pressure assembly incorporating a chest counter-pressure garment and anti-G trousers, which may have extended body coverage, and use a demand breathing regulator that provides protection against hypoxia but also delivers positive PBG. The chest coverage element of the counter-pressure assembly can be inflated to make PBG more tolerable, and following a high-altitude decompression, the anti-G trousers can be inflated as part of the altitude protection system. Linkage between the breathing regulator and the anti-G valve automatically controls these functions, delivering the breathing gas at the pressure appropriate to requirements for altitude and G protection.

REFERENCES

1. Michels DB, West JB. Distribution of pulmonary ventilation and perfusion during short periods of weightlessness. *J Appl Physiol* 1978;45(6):987–998.
2. Haswell MS, Tacker WA, Balldin UI, et al. Influence of inspired oxygen concentration on acceleration atelectasis. *Aviat Space Environ Med* 1986;57:432–437.
3. Tsukimoto K, Mathieu-Costello O, Prediletto R, et al. Ultrastructural appearances of pulmonary capillaries at high transmural pressures. *J Appl Physiol* 1991;71(2):573–582.
4. West JB, Colice GL, Lee YJ, et al. Pathogenesis of high-altitude pulmonary oedema: direct evidence of stress failure of pulmonary capillaries. *Eur Respir J* 1995;8(4):523–529.
5. Prisk GK, Guy HJB, Elliott AR, et al. Pulmonary diffusing capacity, capillary blood volume, and cardiac output during sustained microgravity. *J Appl Physiol* 1993;75(1):15–26.
6. West JB, Hackett PH, Maret KH, et al. Pulmonary gas exchange on the summit of Mount Everest. *J Appl Physiol* 1983;55(3):678–687.
7. Caruana-Montaldo B, Gleeson K, Zwillich CW. The control of breathing in clinical practice. *Chest* 2000;117:205–225.
8. Air Medical Service. *War Department: Air Services Division of Military Aeronautics*. Washington, DC: Government Printing Office, 1919; 423–434.
9. Bryan CL, Jenkinson SG. Oxygen toxicity. *Clin Chest Med* 1988;9(1):141–152.

RECOMMENDED READINGS

West JB. *Pulmonary pathophysiology–the essentials*, 5th ed. Baltimore: Lippincott Williams & Wilkins, 1997.

West JB. *Respiratory physiology–the essentials*, 6th ed. Baltimore, Lippincott Williams & Wilkins, 1999.

CHAPTER 3

Physiology of Decompressive Stress

Jan Stepanek and James T. Webb

> . . . upon the withdrawing of air . . . the little bubbles generated upon the absence of air in the blood juices, and soft parts of the body, may by their vast numbers, and their conspiring distension, variously streighten in some places and stretch in others, the vessels, especially the smaller ones, that convey the blood and nourishment: and so by choaking up some passages, . . . disturb or hinder the circulation of the blouod? Not to mention the pains that such distensions may cause in some nerves and membranous parts..
>
> —*Sir Robert Boyle, 1670, Philosophical transactions*

Since Robert Boyle made his astute observations in the 17th century, humans have ventured into the highest levels of the atmosphere and beyond and have encountered problems that have their basis in the physics that govern this environment, in particular the gas laws. The main problems that humans face when going at altitude are changes in the gas volume within body cavities (Boyle's law) with changes in ambient pressure, as well as clinical phenomena secondary to formation of bubbles in body tissues (Henry's law) secondary to significant decreases in ambient pressure. In the operational aerospace setting, these circumstances are of concern in high-altitude flight (nonpressurized aircraft >5,486 m (18,000 ft), rapid decompression at altitude, flying after diving, and in space operations in the context of extravehicular activities (EVAs). This chapter will focus on pressure changes occurring in the aerospace environment, the associated pathophysiology, pathology, and avenues for risk mitigation and treatment.

Although diving decompression illness and altitude decompression illness are evolved gas disorders, they have very distinct dynamics and clinical pictures as a result of the different gas dynamics and physics; the discussion in this chapter will focus on altitude decompression illness as opposed to diving decompression illness.

For a detailed discussion of acute hypoxia, hyperventilation, and respiratory physiology the reader is referred to Chapter 2, for details on the operational space environment and the potential problems with decompressive stress see Chapter 10, and for diving related problems the reader is encouraged to consult diving and hyperbaric medicine monographs.

THE ATMOSPHERE

Introduction

Variations in Earthbound environmental conditions place limits and requirements on our activities. Even at sea level, atmospheric environmental conditions vary considerably due to latitude, climate, and weather. Throughout the range of aerospace operations, crewmembers and their craft face even larger variations in atmospheric properties that require life support systems and personal equipment for survival and preservation of optimal function. Understanding the physical nature of our atmosphere is crucial to understanding how it can affect human physiology and what protective measures must be employed.

Constituents and Properties of the Atmosphere

The standard atmosphere of Earth at sea level pressure is expressed as 760 millimeters of mercury (mm Hg), which

TABLE 3-1

[a]The Atmosphere of Earth

Gas	*Percentage in Atmosphere*	*Partial Pressure (mm Hg)*
Nitrogen	78.084	593.44
Oxygen	20.948	159.20
Argon	0.934	7.10
Carbon dioxide	0.031	0.24
Other gases	0.003	0.02
Total	100.000	760.00

[a]Clean, dry air at 15°C (59°F), sea level; mean of values every 15° between 15° N and 75° N; Ref: U.S. Standard Atmosphere, 1962.

is equivalent to 1,013.2 millibars [mb or hectoPascals, hPa, hundreds of Pascals (newtons per square meter)], 14.7 psi, and 29.92 in. of Hg. Constituents of the atmosphere we breathe are shown in Table 3-1 and these percentages are consistent throughout the atmosphere of interest to aerospace physiology.

Atmospheric Zones

Temperature and its variation provide much of the basis for subdivisions of Earth's atmosphere into regions defined in Figure 3-1. The lowest zone, the *troposphere*, is the only region of Earth's atmosphere capable of supporting human habitation without artificial support. The troposphere starts at the Earth's surface and extends to the *tropopause*, between 5 and 9 mi [8 to 14.5 kilometer (km); 26,000–48,000 ft]. At its higher levels, above 20,000 ft (3.8 mi; 6 km), at least some degree of artificial support is required in the form of supplemental oxygen. A linear decrease in temperature characterizes the troposphere from sea level (15°C) to the tropopause, typically at approximately 35,000 ft (10.7 km), where the temperature is approximately −55°C. The lapse rate, that is, the rate of decreasing temperature with increase in altitude in the troposphere, is −2°C or approximately −3.5 F per 1,000 ft. Approximately 80% of the atmospheric mass and most of the weather phenomena occur in the troposphere. Variations in temperature, pressure, and humidity in the troposphere account for extreme differences in the environmental conditions we experience as weather.

The tropopause is the division between the troposphere and stratosphere. Aircraft jet engines perform with greater efficiency at lower temperatures, which is one reason cruise is planned near the tropopause where the temperature is lowest. The *stratosphere* starts just above the tropopause and extends up to 50 km (31 mi). Ninety-nine percent of the mass of the air is located in the troposphere and stratosphere. The temperature throughout the lower part of stratosphere is relatively constant. Compared to the troposphere, this part of the atmosphere is dry and less dense. The temperature in this region increases gradually to −3°C due to the absorption of ultraviolet (UV) radiation. This radiation reaching the lower stratosphere from the sun is responsible for creation of ozone, the ozone layer, or ozonosphere. In the process of ozone production and in reactions with ozone, nearly all of the UV radiation is absorbed including the most hazardous form to life, UV-C (wavelengths <280 nm). Much of UV-B (wavelengths between 280 and 320 nm) is also absorbed, although the UV-B reaching the surface is sufficient to be a major cause of melanoma cancers and sunburn. Most of the UV-A (wavelengths between 320 and 400 nm) reaches the Earth's surface, but is needed by humans for production of vitamin D. Although flight in the upper troposphere and lower stratosphere involves exposure to more UV radiation than on the surface, no health risk is currently associated with routine flying operations (see Chapter 8). Flight above the stratosphere and space flight involve risk of exposure to significant levels of radiation.

The higher regions of the atmosphere, 50,000 ft and above, are so thin that pressure suits are required to sustain life. Temperature variations result from variable absorption of the sun's energy in several forms and thermal protection must be incorporated for any exposure in these regions. In the higher regions, flight of air-breathing aircraft becomes impossible and control surfaces are no longer effective. Further description will be left to the references and recommended reading.

The subdivision of the zones described in the preceding text relates to the ability of humans to function based on the partial pressure of oxygen available and need for artificial pressure to sustain life (Table 3-2).

Altitude

Altitude is measured in many different ways using different standards for different purposes. On low-altitude maps provided to pilots, the height of physical features of Earth, like mountains and airfields, is measured in feet above mean sea level (MSL). MSL is the average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings. With properly set, calibrated, and functioning altimeters, feet above MSL is the altitude viewed by the pilot in an aircraft. This is also known as *pressure altitude* (PA), the altitude in the Earth's atmosphere above the standard datum plane, standard sea level pressure, measured by a pressure altimeter. Pilots are quite interested in the height of their aircraft above the ground. This altitude, above ground level (AGL), is determined by subtracting the elevation in feet above MSL of the ground below the aircraft from the elevation of the aircraft. The routine determination of a safe altitude on a route between navigational aids to avoid terrain and towers is usually viewed on low-level navigational maps as the minimum en route altitude (MEA), which is the altitude between radio fixes that assures acceptable navigational signal coverage and meets obstruction clearance requirements between those fixes. Flying at that altitude with a properly set altimeter ensures adequate separation from obstacles for the entire route segment. PA is the height in the atmosphere at which a given value of standard pressure exists. With 29.92 in. of Hg set in the Kollsman window of the

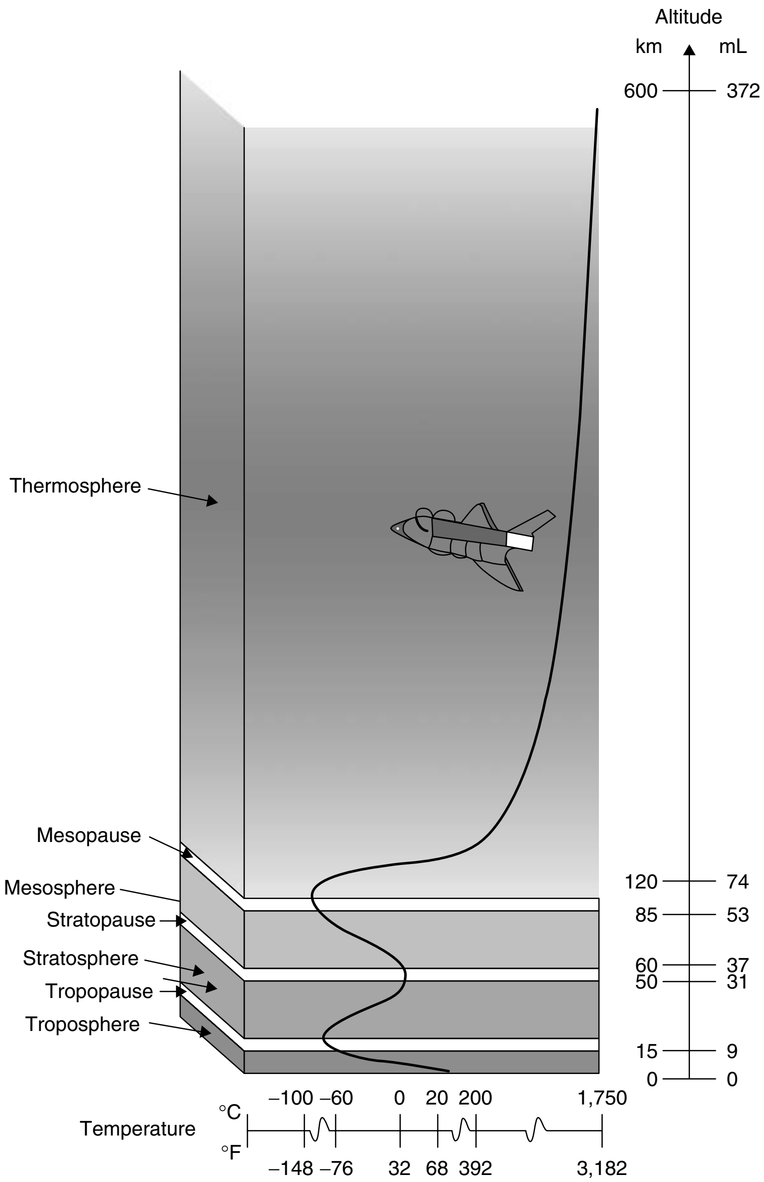


FIGURE 3-1 Zones of Earth's atmosphere.

altimeter, PA is displayed in feet on the altimeters of United States Air Force (USAF) aircraft. Because hectoPascals are a standard in parts of the world, some confusion can arise when pilots "assume" that, for example, 988 means 29.98 in. of Hg when given by an air traffic controller as an altimeter setting because some controllers in the United States leave off the "2."

Air Density, Pressure, and Temperature

The density of air is affected by its pressure, which decreases exponentially with increasing altitude, reaching 50% of sea level density and pressure at approximately 18,000 ft (5.49 km). This relationship is affected in any specific locale by deviations from standard temperature and pressure. Figure 3-2 graphically shows how atmospheric pressure is affected by altitude. The curve depicts how each 10,000-ft increase in altitude results in less change in pressure; 0 to 10,000 ft changing by 237 mm Hg, 10,000 to 20,000 ft changing by 173 mm Hg, and 40,000 to 50,000 ft changing by only 54 mm Hg.

During takeoff, landing, and low-level phases of flight, aircraft altimeters are routinely set to the field altimeter setting to account for variations in local pressure. This procedure avoids significant errors in altitude of the airfield versus what is indicated on the altimeter. Temperature variations from the standard temperature of 15°C also produce errors, which affect terrain clearance. For instance, an aircraft flying at 5,000 ft in −40°C (e.g., Alaska in the winter) would be more than 1,200 ft lower than the indicated altitude *after* correction for local barometric pressure (P_B). Local P_B in the United States is based on inches of Hg. This setting would show the altitude of 0 ft at sea level on such a day. As the local pressure varies, altimeters are set to higher or lower settings to yield the correct field elevation on an aircraft altimeter at a designated point on that field. Above 18,000 ft (flight level 180; altitude in ft/100), altimeters

TABLE 3-2

Physiological Divisions of the Atmosphere

Physiological Division	*Altitude and Pressure Range*	*Problems*	*Solutions*
Physiological zone	0–10,000 ft 0–3,048 m 760–523 mm Hg	Trapped gas expansion/contraction during changes in pressure result in middle ear or sinus blocks; shortness of breath, dizziness, headache, or nausea in unacclimatized individuals or with exercise	Acclimatization or reduced performance
Physiologically deficient zone	10,000–50,000 ft 3,048–15,240 m 523–87 mm Hg	Oxygen deficiency progresses from minor reductions in cognitive and physical capabilities at 10,000 ft to death over approximately 25,000 ft (possibly lower) without supplemental oxygen	Supplemental O_2 and PBA allows good performance to approximately 35,000 ft with progressively less capability
Space equivalent zone	Above 50,000 ft >15,240 m <87 mm Hg	Survival requires assisted PBA[a] or, above approximately 63,000 ft, a full pressure suit and delivery of 100% O_2 to supply at least 140 mm Hg O_2	Pressurized cabin or pressure suit with 100% O_2

[a]PBA = positive pressure breathing for altitude.
(Physiological Training, Air Force Pamphlet 160–5, 1976.)

are routinely set to 29.92 in. of Hg to provide adequate and standardized clearance for aircraft altitude separation. Although the inches of Hg standard for altimeter settings are a pressure indication, it is not normally used in aviation for describing total atmospheric pressure at a given altitude. Elevation is typically measured in ft, meters (m), or km and pressure in psia, mm Hg, or mb.

Light and Sound

Diffusion of light in the lower atmosphere accounts for the blue color of the sky as viewed from Earth's surface, a phenomenon which significantly dissipates as low as approximately 50,000 ft where the blackness of space begins to become apparent. The speed of sound is 761 mph (340 m/s; 1,116 ft/s) at sea level and slower, 660 mph (295 m/s) at 50,000 ft where the temperature is approximately 75°C lower. The speed of sound is a function of the square root of the temperature in °K (°C + 273).

The Gas Laws

A basic understanding of the gas laws is necessary to comprehend the physical nature of the atmosphere and how it interacts with human physiology. The gas laws define physical properties of our atmosphere and provide a basis for understanding how they affect our function during exposure to reduced atmospheric pressure.

Boyle's Law

Robert Boyle (1627–1691) was an Anglo-Irish scientist noted for his work in physics and chemistry. In 1662, Boyle published the finding which states that at a constant temperature, the volume of gas is inversely proportional to its pressure. P_1 and V_1 are the initial pressure and volume, and P_2 and V_2 are the final pressure and volume. Solving this equation for the volume of a contained gas at a different pressure quantitatively describes trapped gas expansion with reduced pressure.

$$P_1 \times V_1 = P_2 \times V_2 \text{ or } P_1/P_2 = V_2/V_1$$

Solving this equation to find the volume of a liter of dry gas taken from sea level to 20,000 ft and 40,000 ft, assuming unrestricted expansion, would result in the following:

1.0 L at sea level

(760 mm Hg ×1 L)/349 mm Hg = 2.2 L at 20,000 ft

(760 mm Hg ×1 L)/141 mm Hg = 5.4 L at 40,000 ft

The problem becomes more complicated by the inclusion of water vapor in the lungs and other spaces in the body as

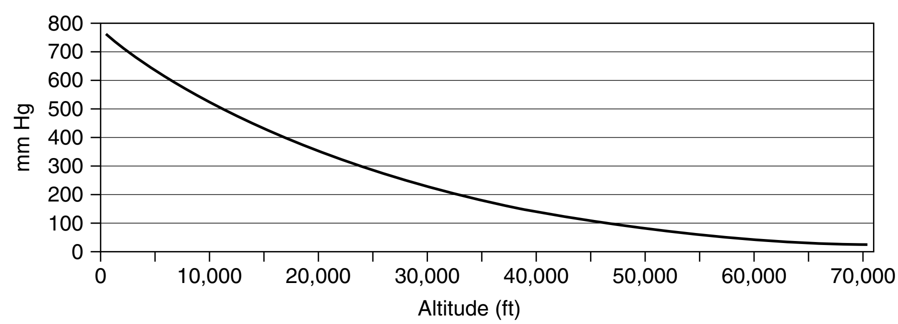


FIGURE 3-2 Atmospheric pressure versus altitude.

described in the section Trapped Gas, Section 3. Figure 3-4 shows the volume and diameter of a wet gas sphere at various pressures and graphically shows how Boyle's law works on trapped gases during decompression and recompression, descent.

Dalton's Law

John Dalton (1766–1844) was an English chemist and physicist. In 1803, he observed that the total pressure of a mixture of gases is equal to the sum of the partial pressures of each gas in the mixture.

$$P_T = P_1 + P_2 + P_3 + \ldots P_n$$

Because the standard atmosphere at sea level is 760 mm Hg, Dalton's law indicates that the sum of partial pressures of the gases that make up the standard atmosphere must equal 760 mm Hg. The pressure of each gas in a mixture of gases is independent of the pressure of the other gases in that mixture. Multiplying the percentage of a gas in the mixture times the total pressure of the mixture yields the partial pressure of that gas.

The standard atmosphere does not include water vapor pressure, primarily due to its variation in the Earth's atmosphere between 0% and 100% relative humidity. This variation amounts to 0% to 6.2% of 760 mm Hg, or 0 to 47 mm Hg at body temperature, 37°C.

Henry's Law

William Henry (1775–1836) was an English chemist who, in 1803, published his findings that the amount of a gas in a solution varies directly with the partial pressure of that gas over the solution. This relationship explains why dissolved nitrogen transitions to a gas phase in blood and tissues during decompressions sufficient to result in supersaturation. The resulting bubbles of nitrogen with minor amounts of oxygen, carbon dioxide, and water vapor can cause decompression sickness (DCS).

Charles and Gay-Lussac's Law

Jacques Alexandre César Charles (1746–1823) was a French inventor, scientist, mathematician, and balloonist. In 1783, he made the first balloon using hydrogen gas; upon release, it ascended to a height of approximately 3 km (2 mi). In 1787, he discovered the relationship between the volume of gas and temperature, known variously as *Gay-Lussac's law* or *Charles's law*.

$$V_1/V_2 = T_1/T_2 \text{ or } V_1/T_1 = V_2/T_2$$

Charles did not publish his findings and Joseph Louis Gay-Lussac first published the finding in 1802, referencing Charles' work. The temperature is in Kelvin degrees, where $°K = °C + 273$. At absolute zero, $-273°C$, the Kelvin temperature is 0°K. The distinction between Boyle's law and Charles' law is what is held constant, whereas the other two parameters are varied. Boyle's law describes changes in volume with respect to pressure when temperature is held constant. Charles' law describes how volume changes with temperature when pressure is held constant. Although Charles' law is very important from an engineering and chemistry standpoint, the temperature of human body is usually rather constant at body temperature, limiting its effect on physiology. Changes in all three parameters (volume, pressure, and temperature) are better described by the Ideal Gas law, which includes the three parameters in one equation with other factors to improve accuracy.

$$PV = nRT$$

where P = pressure, V = volume, T = temperature, n = number of moles, and R = universal gas constant = 8.3145 J/mol K.

Gaseous Diffusion

Experiments of Thomas Graham (1805–1869), a British chemist, showed that the diffusion of a gas is inversely proportional to the square root of its molecular weight. Therefore, gases of lower molecular weight diffuse more rapidly than gases of higher molecular weight. Diffusion of a gas is also affected by its solubility in the surrounding media and the difference in concentration of the gas between two adjacent volumes. A larger difference in concentration produces greater diffusion. A gas with greater solubility in its solvent, for example tissue or fluids, means more molecules of it will be available to diffuse as limited by the other factors. Gaseous diffusion is fundamental to the physiologic processes of lung and cellular respiration. It further applies to the process of denitrogenation, removal of nitrogen from the body, by breathing 100% oxygen.

Chronic Hypoxia

Terrestrial Environment

The historical distinction between hypoxia in the terrestrial and extraterrestrial/aerospace environment has become increasingly blurred in recent decades. The time at a certain pressure (i.e., altitude) and the time and modality to get to that pressure govern the physiology that will be discussed. The advent of ultra–long-haul flight operations in environments of decreased ambient pressure in civilian air transport operations (1) and potentially in future exploration class spaceflight missions, as well as rapid transport of civilian and military personnel to and prolonged sojourn in high-altitude environments make it very important for the aerospace medicine practitioner to be familiar with the concepts of operational significance that can play a role in those environments. The following paragraphs will review operational considerations and relevant clinical terrestrial syndromes.

Acclimatization

Altitude acclimatization is a process that occurs upon exposure to a hypobaric and hypoxic environment. Different processes occur with the common goal to protect the body tissues against the hypoxic challenge of the environment and

TABLE 3-3

Processes of Acclimatization and Relevant Terminology

Acute Acclimatization (Accommodation)	*Minutes*	*Rise in Heart Rate, Increased Ventilation*
Chronic acclimatization	Days	Increase in hemoglobin (initial decrease in plasma volume followed by increased red cell mass), increased capillary density
Adaptation	Years	Alterations in hypoxic ventilatory response

to allow for continued performance. Many of these processes occur at different speeds and can be summarized in different groupings (Table 3-3).

Owing to the processes discussed in the preceding text, it is difficult to answer the simple question as to how much time is needed to acclimatize to a given altitude, but the key aspects in acclimatization rest in the cardiorespiratory system and the blood that adapt in days to few weeks.

Unfortunately, there is no one single parameter that allows us to physiologically quantify and assess the level and degree of acclimatization. In addition to the lack of a single reliable parameter to assess acclimatization, we are faced with significant interindividual variation in speed and degree of acclimatization. A good clinical rule is to always inquire about past performance at altitude and presence or absence of signs and symptoms of acute mountain sickness (AMS); past performance is a guide to future performance in similar environments and exposures. Special attention needs to be given to any preexisting cardiac or pulmonary disease or conditions that may be exacerbated by exposure to a hypoxic environment.

There are only scarce data addressing acclimatization and the effects of age and gender. There does not appear to be a significant difference in acclimatization between men and women, and older age appears to confer some protection from AMS.

Preacclimatization is a technique used to achieve some degree of acclimatization preceding the exposure in the high-altitude environment. This can be accomplished by using an analog environment such as an altitude chamber or sojourns at altitude; good data to show consistent acclimatization benefit of intermittent hypoxic exposures with nitrogen admixture to the breathing gas (e.g., sleeping in a hypoxic environment) are lacking at this point. The benefits of acclimatization appear to dissipate over a period of 2 to 3 weeks, and it should be noted that pulmonary edema has been described in native highlanders with reexposure to altitude after as little as 12 days at low altitude (2).

Operational Considerations

Reduced Exercise Capability

Aerobic performance is significantly impaired as altitude and maximal oxygen consumption in acclimatized subjects falls from 4 to 5 L/min to approximately 1 L/min at the altitude of Mount Everest. The demands of the hypoxic environment lead to a significant reduction in exercise capacity and many an account of expeditions at extreme altitudes, especially without supplemental oxygen, is filled with vivid descriptions as to the extreme difficulty of exercise (3).

Any attempt to exercise or be physically active at high altitude is accompanied by markedly elevated levels of ventilation. It is noteworthy that ventilation is usually expressed with reference to ambient pressure, body temperature, and with the gas saturated with water vapor [referred to as *body temperature and pressure saturated* (BTPS)]. This measurement reference takes into account more accurately the volume of gas moved by the chest and lungs. Another measurement condition is STPD, which stands for the measurement of ventilation in conditions of **S**tandard **T**emperature, **P**ressure, and **D**ry gas. The latter shows much smaller volume changes at altitude and has no overt relationship to the actual mechanics of breathing (lung/chest wall movements). Oxygen consumption and carbon dioxide production are traditionally reported in STPD reference units, such that the values are altitude independent.

Ventilation measurements at high altitudes can reach near maximum voluntary ventilation levels driven by the powerful hypoxic drive through the peripheral chemoreceptors; during the 1981 Everest expedition at 8,300 m (Pb 271 mm Hg), Pizzo recorded maximum ventilation with a respiratory rate of 86 breaths/min and a tidal volume of 1.26 L/min resulting in a mean ventilation of 107 L/min (4,5).

Reduced Cognitive Ability

The exposure to any hypoxic environment has operational ramifications in that it can sharply reduce the effectiveness of an operator, especially in the first few days following insertion into a high-altitude terrestrial environment. Especially in the first week at altitude, consideration should be given to adequate rest periods (taking into account the temporary degradation of sleep quality at altitude), decreased task intensity, and if possible decreased operational tempo. In addition to the known decrements in cognitive performance associated with varying degrees of hypoxia, the development of severe headaches and neurologic symptoms and signs, as well as pulmonary symptomatology may be harbingers of a clinically relevant high altitude–related illness such as high-altitude cerebral edema (HACE) or high-altitude pulmonary edema (HAPE).

Relevant Clinical Terrestrial Syndromes Related to High Altitude

The emphasis in the discussion of high altitude–related clinical syndromes must be prevention. The hostile environment of extreme high altitudes coupled with the intense desire to accomplish a set goal (e.g., climbing a mountain, executing a mission) in the context of highly motivated and driven team members may at times be a dangerous combination.

The education of all team members about disease entities and their symptoms that can arise at high altitudes (6,7) is of importance such that everybody may be able to observe their team members and peers. The emergence of any concerning signs or early behavioral alterations such as falling behind, change in attitude, lethargy, and so on should prompt heightened vigilance and early evaluation. Monitoring the dynamics of any signs and symptoms will allow the team to avoid bad outcomes, and to enable any team member with worsening symptoms to descend while they are still able to walk.

Acute Mountain Sickness

AMS is a syndrome encompassing headache, anorexia, lassitude, nausea, and a feeling of malaise. It can be encountered in 15% to 30% of Colorado resort skiers (8) and in up to 67% of climbers on Mount Rainier (9). Many people become symptomatic even at intermediate altitudes of 6,000 to 6,500 ft. Rapid ascent to altitude (flying, driving) may markedly exacerbate the risk. Symptoms usually manifest within hours to first few days at altitude.

The scoring of AMS can be accomplished by using Lake Louise consensus scale or a subset of questions of the environmental symptom questionnaire (ESQ). The ESQ consists of 67 questions in its ESQ III version. Clinically, it is most relevant to insist that headache be present for the diagnosis of AMS. Most practitioners prefer the Lake Louise scoring system due to its simplicity, consisting of a self-assessment (most important), clinical assessment, and afunctional score. Symptomatic therapy with nonsteroidal anti-inflammatory over-the-counter medications relieves the symptoms of headaches. Use of acetazolamide (a carbonic anhydrase inhibitor) is useful in the treatment of symptoms, but more importantly in the prophylaxis of the condition. The latter is advisable if historically a subject has had past episodes of severe mountain sickness or rapid exposure to a significant altitude is expected. Carbonic anhydrase inhibitors will facilitate acclimatization to altitude. Other agents can be used for symptom control, such as dexamethasone or other steroids. The disadvantage of using steroids for the treatment of mountain sickness is their lack of effect on acclimatization and their side effect profile. A rebound effect, that is, reoccurrence of mountain sickness after cessation of steroids at altitude is possible.

If available oxygen will alleviate symptoms of mountain sickness, severe cases may benefit from use of a portable hyperbaric chamber (10), especially in the setting of high-altitude expeditions.

The occurrence of the ataxia in a subject with severe mountain sickness should be taken very seriously as it may be a harbinger of early high-altitude cerebral edema, which if present may preclude safe self-evacuation by going to lower altitude.

High-Altitude Cerebral Edema

HACE usually occurs several days after altitude exposure in the context of mountain sickness. The differentiation between severe mountain sickness and HACE rests in the development of ataxia, impaired cognition, and higher cortical functions (hallucinations, inability to make decisions, severe mental slowing, irrational behavior, errors) as well as neurologic deficits in addition to the symptoms of severe mountain sickness as described earlier (11).

The occurrence of HACE in a hostile high-altitude environment will incapacitate the patient and lead to the need of an evacuation, thereby putting other participants potentially at risk. Avoidance of passive transport to extreme altitude and avoidance of ascending with symptoms of mountain sickness are important factors to avoid unnecessary bad outcomes. HACE may occur together with HAPE. Treatment of HACE consists of descent, the administration of steroids (e.g., dexamethasone), oxygen, and if available, use of a portable hyperbaric chamber with the goal of rendering the patient ambulatory, thereby allowing for further descent from altitude.

High-Altitude Pulmonary Edema

HAPE is a noncardiogenic pulmonary edema, which can occur in up to 1% to 2% of subjects at 12,000 ft (3,650 m), and there appears to be a genetic predisposition in some patients. A careful history will allow identification of this subpopulation. Significant exaggerated elevations of pulmonary arterial pressures in susceptible subjects in response to hypoxia at altitude appear to be causal factors in the pathogenesis of this condition.

Incidence depends on rate of ascent and peak altitude reached; reports from Pheriche (4,243 m) showed an incidence of 2.5% (12); Indian troops flown to an altitude of 3,500 m had an incidence of 0.57% (13).

Symptoms of HAPE are breathlessness, chest pain, headache, fatigue, and dizziness. Signs include mild elevation of temperature, dry cough (especially on exertion), hemoptysis, tachycardia, tachypnea, and cyanosis.

X-rays frequently reveal a pattern of irregular, patchy, later confluent infiltrates in both lower- and mid-lung fields, whereas the apices can be spared at times.

Lowering the pulmonary arterial pressures to provide relief can be accomplished with oxygen and vasodilators such as nifedipine and other agents such as phosphodiesterase inhibitors, which are currently under study for clinical use in this condition.

For individuals that have genetic disposition to this condition, use of prophylactic nifedipine may be a viable option to prevent HAPE.

Alternatively, the ambient pressure can be increased in a portable hyperbaric chamber to achieve improvement and thereby allow for transportability to lower altitude.

Chronic Mountain Sickness (Monge's Disease)

Chronic mountain sickness is a disease entity that can be found in populations remaining at altitude for many years. The key findings include erythrocytosis and related symptoms such as headaches, dizziness, physical fatigue and mental slowing, anorexia, and dyspnea on exertion, cyanosis, and a ruddy complexion. Pulmonary hypertension and right heart failure may also be present. Obvious contributing causes would be chronic obstructive lung disease, obstructive sleep apnea or sleep-disordered breathing conditions causing hypoxia, and other pulmonary pathology, making the patient more hypoxic and thereby enhancing the erythrocytosis even further. Relocation to low altitude in the absence of pulmonary pathology or other contributing causes is usually curative.

Laboratory investigations reveal an increased red cell count, hemoglobin concentration, and packed red blood cell volume. Pa_{O_2} is decreased and P_{CO_2} is elevated. The increase in alveolar–arterial oxygen tension gradient is likely attributable to increased blood flow to poorly ventilated areas. The electrocardiogram shows right ventricular hypertrophy and increased pulmonary arterial pressures as well as blood viscosity (14–17).

High-Altitude Retinal Hemorrhages

High-altitude retinal hemorrhages (HARH) may be seen in many climbers at very high altitude. The hemorrhages are typically without symptoms and tend to disappear spontaneously over a couple of weeks upon return from altitude. There appears to be a correlation between retinal hemorrhages and HACE (16,17). The subject may develop symptoms if these hemorrhages are close to the macula. The distribution of these hemorrhages and cotton wool spots is of a periarteriolar and perivenous distribution. Typically, no treatment is required and recovery is spontaneous.

High-Altitude Deterioration

Extended stays at altitudes greater than 5,000 m typically result in significant weight loss. Field studies and observations from expeditions certainly introduce a variety of confounding factors, such as cold, limited food supplies or lack of palatable food, or the increased need to burn calories for activities of climbing or walking. It is remarkable that similar observations were made in altitude chamber studies, such as the Operation Everest studies that were 40 days in length, and revealed, despite an unlimited diet and comfortable environmental conditions, that the subjects still lost weight. An increase in basal metabolic rate has been invoked as a causal factor. Furthermore, changes in intestinal absorption of carbohydrates, protein, and fat in the context of hypoxia may also play a role above 5,000 m (15).

Extraterrestrial Environment

Activity outside of the habitat will be required on a regular basis from any Moon- or Mars-based facility to accomplish the objectives of exploration. The pressure suit used during exploration must keep the explorer functional in the absence of an atmosphere on the Moon and near vacuum (4.5 mm Hg) on the surface of Mars. The suit should have as little negative impact on the mission as possible, which means freedom of movement and minimal fatigue. Current National Aeronautics and Space Administration (NASA) EVA suits employ 100% oxygen at 4.3 psia (226 mm Hg) (18,19), which provide more oxygen than available in sea level air. These current suits are too restrictive and heavy for use on Mars or the Moon, and unless dramatic advances in suit technology are achieved, a 4.3 psia EVA suit pressure may not be feasible. Therefore, a much lower suit pressure may need to be considered. Avoiding DCS during the transition from habitat pressure to a suit pressure below approximately 3.7 psia (192 mm Hg) would also require a lower habitat pressure. A hypoxic environment in the habitat and during exploration could be experienced on a daily basis. Some physiologic changes will occur, which are analogous to terrestrial altitude-induced changes.

Adaptive Changes to a Hypobaric Hypoxic Environment

Adaptation to a low level of hypoxia in an artificial habitat environment (acclimation) could be tolerated the same way acclimatization allows thousands of humans to visit or live at high-terrestrial altitudes (3,100 m; 519 mm Hg, 10,200 ft) without supplemental oxygen. Although considerable improvement in function occurs after a few days of exposure to 3,100 m, ventilatory acclimatization would take about a week (20,21). Low gravitational forces on the Moon and Mars may reduce the workload and effect of any hypoxia during routine activity. Although the lower gravity on Mars (38% of Earth) may reduce the impact of pressure suit weight, mass is still a potential problem in terms of momentum and balance during exploration. Many factors will determine the potential atmospheres of Moon and Mars habitats, although some degree of acclimation to hypoxia is likely to be necessary.

Lower Total Pressure

Any reduction in total pressure reduces the effectiveness of electronic cooling fans and complicates atmospheric control and circulation. The engineering challenge must meet the need for close tolerances on levels of humidity, carbon dioxide, and oxygen levels to maintain comfort and physiologic function. Detection and removal of pollutants should be an extrapolation and refinement of the progress made during the International Space Station (ISS) habitation.

Water Balance

Maintenance of a comfortable level of humidity in a low-pressure habitat, for example 40% relative humidity and a temperature at 20°C (68°F), could help to reduce respiratory losses of water. This level of humidity with relatively full coverage clothing would also aid in reducing insensitive water loss.

Operational Considerations

Reduced Cognitive Ability

Acute exposure to 3,048 m (523 mm Hg, 10,000 ft) in Earth's atmosphere produces documented decrements in some cognitive tests (22,23), particularly those involving learning new tasks. In another study, 12-hour exposures to 10,000 ft (3,048 m) with rest or mild exercise produced no significant negative impact on cognitive function, but minor negative effects were observed on night vision goggle performance under operational lighting (starlight) conditions. Increased reports of headache during the resting exposures at altitude may indicate imminent mild AMS (24). The USAF does not require its aircraft pilots to use supplemental oxygen at or below 10,000 ft during their routine acute exposures.

Reduced Exercise Capability

Even after acclimatization, maximal oxygen uptake is lower at 10,000 ft than at sea level for any individual (25). However, the effect on the submaximal effort during extraterrestrial exploration is unknown.

Communication

A reduced total pressure for a Moon or Mars habitat and pressure suits will affect vocal cord efficiency in sound development, although above a total pressure of 226 mm Hg (4.4 psi; 30,000 ft), verbal communication has not been a problem. Because communication between pressure-suited explorers will require electronic transfer, appropriate amplification and filtration could compensate for lower vocal cord efficiency at suit pressures in the 141 mm Hg (2.7 psia; 40,000 ft) range.

Fire Safety

The National Fire Protection Association (NFPA) has developed an equation that allows calculation of the maximum percentage of oxygen that avoids designation as an atmosphere of increased burning rate. The NFPA 99B: Standard for Hypobaric Facilities (2005;3.3.3.3) defines atmosphere of increased burning rate on the basis of a 12 mm/s burning rate (at 23.5% oxygen at 1 atmospheres absolute (ATA). The equation defining such an atmosphere (NFPA 99B Chapter 3 Definitions; 3.3.3.3) is:

$$23.45/(\text{Total Pressure in Atmospheres})^{(0.5)}$$

The factor 23.45 is the highest percentage of oxygen at sea level, which does not create an atmosphere of increased burning rate.

Even if a pressurized transportation system were used on the surface, continuous wear of a pressure suit would likely be required to provide adequate safety in the event of pressurization failure. The pressure suit must be designed to provide a sufficient level of oxygen and total pressure (minimum of approximately 141 mm Hg O_2; 2.7 psia) to allow normal physiologic function of an acclimated individual and for extensive mobility and maneuverability. If a pressure suit employing as much as 4.3 psi differential cannot be made to meet these requirements, a lower suit pressure may need to be considered.

Decompression illness (DCI) is a term used to encompass DCS and arterial gas embolism (AGE). DCS is a clinical syndrome following a reduction in ambient pressures sufficient to cause formation of bubbles from gases dissolved in body tissues. DCS follows dose–response characteristics at each involved tissue-site, the pathophysiological sequence that may or may not follow, and clinical symptoms that may occur subject to multiple moderating factors (environmental and operational tissue factors as well as marked individual susceptibility).

Historical Aspects

Sir Robert Boyle did pioneering work in the field of high-altitude medicine and was the first to observe bubble formation *in vivo* in one of his experimental animals during decompression in a hypobaric chamber

> *"I shall add on this occasion . . . what may seem somewhat strange, what I once observed in a Viper . . . in our Exhausted Receiver, namely that it had manifestly a conspicuous Bubble moving to and fro in the waterish humour of one of its Eyes."*

Subsequent clinical evidence of DCS in humans came from air-pressurized mineshaft operations. M. Triger, a French mining engineer, reported in 1841 pain and muscle cramps in coal miners (26). In 1854, two French physicians, B. Pol and T. J. J. Watelle, gave an account of the circumstances in which the disease develops upon exiting the compressed air environment: "One pays only on leaving" and recognized as well that recompression ameliorated the symptoms. They were the first to use the term *caisson disease* named for the compressed air environment the workers were exposed to—analogous to the diving bells (caissons) (27).

In 1869, the French physician L. R. de Mericourt published the first comprehensive medical report on DCS in divers (27). The French physiologist Paul Bert described in his classic treatise *La pression barométrique* (1878) the relationship between bubbles and symptoms of DCS during rapid decompression (28).

The advent of balloons and aircraft with sufficient performance to attain significant altitudes brought the clinical syndrome into the realm of aerospace medicine. In 1906, H. Von Schrötter described in his book *Der Sauerstoff in der Prophylaxe und Therapie der Luftdruckerkrankungen* the symptoms he experienced in a steel chamber after ascending in 15 minutes to 8,994 m (29,500 ft) closely resembling caisson disease (29). Von Schroetter discounted that hypothesis, but Boycott, Damant, and Haldane reviewed his account and wrote in an article in 1908 (30):

> *"Although he concludes that these symptoms could not have been due to caisson disease, we think in view of the data given by Damant and ourselves, that he was probably mistaken, and that the risk of caisson disease at very low pressure ought to be taken into account."*

This is the first clear reference to altitude DCS in the literature. In 1917, Professor Yandell Henderson provided a detailed theory in which he postulated that it would be possible to get DCS from altitude exposure (31).

J. Jongbloed described in his thesis in 1929 (32,33) the effects of simulated altitude on human subjects and called attention to the similarities of compressed air illness and DCS of altitude. In 1931, Barcroft et al. (34) described pain in the knees experienced in the hypobaric chamber while exercising at altitudes of 9,160 m (30,000 ft), which in hindsight were most likely manifestations of DCS. In the United States, Dr. H. Armstrong researched the effects of decreased PB on the aviator and described in 1939 bubble formation that he experienced himself while at altitude in the hypobaric chamber (35):

> "... *Then I noticed a series of small bubbles in the tendons of my fingers ... I was certain in my mind they represented aeroembolism..*"

In 1938, Boothby and Lovelace reported a case of transient paraplegia in a fellow physiologist (Dr. J. W. Heim) during an ascent to 10,670 m (35,000 ft) while on oxygen; the paraplegia disappeared upon repressurization to ground level. This case illustrated the potential for serious neurologic DCS at altitude and spurred more research (36).

The recent decades of research have introduced new monitoring capabilities, which have allowed investigation of the bubble manifestation of the disease under controlled laboratory conditions. Ultrasonic echo-imaging Doppler measurements as an index for gas evolution have enhanced our capability to investigate the *in vivo* venous gas phase. The degree of venous bubbles present is graded on a numerical scale referred to as a *venous gas emboli* (VGE) score. The first such scoring system was devised by Spencer in 1976 (37); on this 0 to 4 scale a score of 0 refers to no bubbles and a score of 4 refers to an observation with numerous bubbles obscuring the heart sounds.

The experimental work carried out in the 1970s and 1980s has shown that bubbles can be detected in the circulation of healthy individuals after decompressions without any clinical signs of DCS (38). This confirms the early hypothesis by Behnke (1947), who postulated the existence of "silent bubbles" (39). The paradigm of "bubbles = DCS" appears not to be true in many, if not most cases, and recent research focuses on the pathophysiological cascade that can be started by the *in vivo* gas phase (bubbles) in the different tissue compartments and the dose–response relationships leading to clinically evident DCS manifestations. This explains why the demonstration of VGE in the cardiac chambers correlates poorly with the development of DCS. A significant proportion of subjects do have detectable VGE, but do not develop DCS and some develop DCS without evident VGE (38). As more research data becomes available, there is a trend to recognize certain degree of DCS as a normal physiological response to a defined time-pressure profile environment with the *caveat* of possible individual predisposition and other factors.

Terminology

The clinical syndrome of DCI was first recognized in the diving/compressed air environment and later found recognition in the area of aerospace medicine; this explains the wide variety of terms used to describe the disorder and certain specific clinical manifestations. The term *decompression sickness* is a direct translation from the German term *Druckfallkrankheit*, which was introduced by Benzinger and Hornberger in 1941 (40). Currently, *altitude decompression sickness* or simply *decompression sickness* is the term most widely used and accepted in the aerospace medicine literature.

Older terms include aeroembolism, aeropathy, dysbarism, high-altitude diver's disease, high-altitude caisson disease, mechanicobaropathy, aerobullosis, and aeroarthrosis. *Decompression illness* is a term that was introduced to encompass DCS and arterial gas embolism. There is also the distinct possibility for VGE to become arterialized either by crossing the pulmonary filter or crossing through a shunting mechanism from right to left side of the heart (41). The term *DCI* should not be used synonymously with DCS to avoid confusion in an area with already broad terminology.

The typical clinical manifestations of DCS have received idiomatic descriptions over time, the classical limb and joint pains are referred to as *bends*, a term that was used by fellow workers to describe the particular gait—"doing the Grecian bend"—of workers emerging from caisson work during the construction of the piers of the Brooklyn Bridge in the 1870s (26). Respiratory disturbances are commonly referred to as the *chokes*, skin irritation as *creeps* or *divers itch*, and disturbances of the central nervous system (CNS) with vestibular involvement have been labeled with the term *staggers*.

There are distinct and very important differences between hyperbaric (diving) DCS and hypobaric (altitude) DCS, despite many shared commonalities in history, pathophysiology, and nomenclature (Table 3-4). This is a very important point as there is a tendency to indiscriminately transfer information and inferences from one field of research to another, which at times may be a valid thing to do, more often than not though may be unwise and not justified, thereby leading to potentially erroneous conclusions.

The operational significance of DCS is different in hyperbaric versus hypobaric operations in that a diver will get DCS after mission completion (ascent to the surface from depth), whereas an aviator will experience DCS during his mission at altitude. Furthermore, the aviator will have the potential to endanger others if he or she loses control of his aircraft due to DCS, whereas the diver will likely be putting only himself as an individual at risk.

BUBBLE FORMATION: THEORETIC CONSIDERATIONS

The physical principle responsible for bubble formation with decreases in ambient pressure is the concept of supersaturation, which is based on Henry's gas law that states that the amount of gas dissolved in any liquid or tissue is proportional to the partial pressure of that gas with which it is in contact. A good example that illustrates the physical characteristics of Henry's law as it applies to DCS is the opening of a bottle of carbonated beverage. Before opening, few, if any bubbles are visible in the liquid as the gas pressure above the liquid is in equilibrium with the liquid,

TABLE 3-4

Differences between Hypobaric (altitude) and Hyperbaric (Diving) Decompressive Stress (DCS)

Relevant Differences between Altitude and Diving DCS	
Altitude DCS	*Diving DCS*
1. Decompression starts from ground level tissue nitrogen saturated state	1. Upward excursions from saturation diving are rare
2. Breathing gas is usually high in O_2 to prevent hypoxia and promote denitrogenation	2. Breathing gas mixtures are usually high in inert gas due to oxygen toxicity concerns
3. The time of decompressed exposure to altitude is limited	3. The time at surface pressure following decompression is not limited
4. Premission denitrogenation (preoxygenation) reduces DCS risk	4. The concept of preoxygenation is generally not applicable
5. DCS usually occurs during the mission	5. DCS risk is usually greatest after mission completion
6. Symptoms are usually mild and limited to joint pain	6. Neurologic symptoms are common
7. Recompression to ground level is therapeutic and universal	7. Therapeutic chamber recompression is time limited and sometimes hazardous
8. Tissue P_{N_2} decreases with altitude exposure to very low levels	8. Tissue P_{N_2} increases with hyperbaric exposure to very high levels
9. Metabolic gases become progressively more important as altitude	9. Inert gases dominate
10. There are very few documented chronic sequelae	10. Chronic bone necrosis and neurologic damage have been documented

Pilmanis AA, Petropoulos L, Kannan N, et al. Decompression sickness risk model: development and validation by 150 prospective hypobaric exposures. *Aviat Space Environ Med* 2004;75:749–759.

on lowering the pressure above the liquid by opening the bottle, the liquid–gas system re-equilibrates to the lowered ambient pressure by offgassing bubbles.

The mechanisms that are involved in the hyperbaric diving environment as well as the hypobaric altitude environment are thought to be the same in regard to DCS, although the bubble dynamics appear to be different. Decompression to altitude results in a slower release of bubbles compared to the same absolute ratio of pressure change in a hyperbaric environment (42).

The current theories of bubble formation involve two main mechanisms. *De novo* formation of bubbles also referred to as *de novo* nucleation, requires very high degrees of supersaturation and formation of bubbles from preexisting gas nuclei (bubble nuclei), which requires pressure differentials of only fractions of an atmosphere.

The current working hypothesis for the formation of *in vivo* bubbles favors the gas nuclei mechanism. Viscous adhesion, which is the mechanism by which negative pressures are generated in a liquid between moving surfaces (e.g., joints), is of sufficient magnitude to cause *de novo* bubble formation. This mechanism has been invoked to explain vacuum phenomena in joints, the cracking of joints, and the formation of autochthonous (*in situ*) bubbles in the white matter of the spinal cord (43). The following discussion will highlight these mechanisms and factors influencing bubble growth.

The mechanisms and moderating factors in the human body tissues that lead to bubble formation/propagation, clinical symptoms of DCS, and moderating variables are still incompletely understood.

Factors Influencing Bubble Formation

Bubble Nuclei

The conceptual idea of the presence of "bubble nuclei" or "bubble formation centers" in the tissues derives from the physics limiting bubble growth. Very small bubbles should have a propensity to dissolve and disappear due to their very high surface tension. Surface tension is inversely proportional to the bubble radius (law of LaPlace), which would raise the internal pressure of the microbubbles above the external absolute pressure, thereby leading to their dissolution. This would suggest that larger bubbles should not be able to exist if there are no smaller bubbles that precede them, which is an obviously wrong conclusion. If we assume that we would need to create bubbles *de novo,* then experimental evidence shows that forces of approximately 100 to 1,400 ATA are needed. We know that bubble formation occurs at much lower pressure differentials in animals and humans (fractions of 1 ATA). Bubbles can form in fluids at low levels of supersaturation if forces act to pull objects apart which are in close proximity, a process called *tribonucleation*. Furthermore there is experimental evidence showing that compression of animals (shrimp, crabs, and rats) before hypobaric exposure markedly decreases bubble formation and DCS (44). These observations are consistent with the existence of gas nuclei that allow bubble formation at much lower pressure gradients (fractions of 1 ATA). The current understanding of the dynamics of bubble nuclei is that they are generated by motion (and possibly other factors, see section **Mechanical Supersaturation** in subsequent text) and that there is a dynamic equilibrium between generation and destruction of gas nuclei in the tissues (45).

Supersaturation

During decompression from any atmospheric pressure, some quantity of inert gas in the tissues must diffuse into the blood, travel to the lungs, and leave the body in the expired air because the quantity of inert gas that can remain dissolved in tissue is directly proportional to the absolute ambient pressure.

Supersaturation is defined by the following equation:

$$\text{Supersaturation} = \sum P_g + \sum P_v - \sum P_a$$

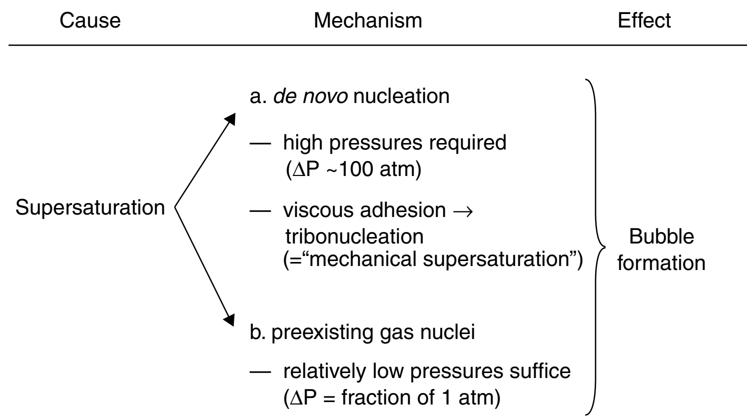


FIGURE 3-3 Synopsis of the different mechanisms involved in bubble formation.

P_g: sum of the tensions of all dissolved gases; P_v: sum of any vapor pressure (e.g., water); P_a: local absolute pressure.

In summary, we can say that supersaturation can occur when either local absolute pressure is low or when the sum of the dissolved gases and vapor pressures is high.

During ascent, the reduction in P_B creates a condition whereby the tissue inert gas tension (P_{N2} = nitrogen gas partial pressure) is greater than the total P_B. This situation is called *supersaturation*. Therefore, if the decompression exceeds some critical rate for a given tissue, that tissue will not unload the inert gas rapidly enough and will become supersaturated. The probability of bubble formation increases with increasing supersaturation.

Supersaturation due to negative pressure occurs in many mechanical processes resulting in a local reduction of absolute pressure in a liquid system. The flow of a liquid through a local narrowing in a tube, for example, results in a local drop in pressure (Bernoulli principle), which in turn can lead to transient bubble formation (Reynold's cavitation). Sound waves are well known to cause acoustic cavitation in liquid systems. A further mechanism of biological interest is viscous adhesion (Figure 3-3). Viscous adhesion describes the forces generated when two surfaces in a liquid are pulled apart; the negative pressures that can be generated can reach thousands of negative atmospheres. The amount of supersaturation that can be mechanically generated by viscous adhesion is directly proportional to the liquid viscosity and indirectly proportional to the cube of the distances between the two surfaces. Bubbles that are generated by this mechanism are said to be generated by tribonucleation. This mechanism is invoked in the generation of the cracking of joints by pulling apart their articular surfaces, resulting in the generation of a vapor-filled bubble, which collapses upon release of the traction, as well as in the appearance of vacuum phenomena (gaseous cavitation) in joints under traction and in the spinal column within disks, facet joints, and vertebrae (43,45).

Critical Supersaturation

Apparently, a level of supersaturation is reached which the body can tolerate without causing the inert gas to come out of solution to form bubbles. Once the critical supersaturation ratio is reached, however, bubbles develop which can lead to DCS. The English physiologist J. S. Haldane first described the concept of critical supersaturation in 1908 (30). Haldane was commissioned by the British Admiralty to investigate and devise safe decompression procedures for Royal Navy divers, and his work demonstrated that humans could be exposed to hyperbaric pressures and subsequently decompressed without having DCS as long as the total pressure reduction was no greater than 50%. Haldane devised the concept of tissue half-time to define the ability of a particular tissue to saturate/desaturate with nitrogen by 50% (i.e., a tissue would be saturated 50% after the passing of one tissue half-time). He postulated that the body tissues with different perfusion rates can be adequately represented by half-times of 5, 10, 20, 40, and 75 minutes (five-tissue model, constant allowable ratio). Haldane argued that the human body could hypothetically tolerate a 2:1 decrease in ambient pressure without getting DCS symptoms ("2-to-1" rule). Further operational research showed that the Haldane diving tables consisting of Table 1 for shorter dives up to 30-minute decompression time and, up to a depth of 204 ft sea water (fsw) and Table 2 for longer dives (with bottom times >1 hour and decompression times of >30 minutes) were overly conservative for Table 1 and not safe enough for Table 2. Current theory is based on variable allowed ratio for different tissues; this is influenced by tissue nitrogen half-time, time, and ΔP. This is the reason why no current decompression schedules use Haldane's 2-to-1 rule, but it is discussed here to show a mathematical concept. If Haldane's 2-to−1 relationship of allowable total pressure change is converted to a P_{N_2} to P_B relationship, the critical supersaturation ratio (R) would be:

$$R = \frac{P_{N_2}}{P_B}$$

For example,

$$R = \frac{P_{N_2} \text{ at } 2\text{ATA}}{P_B \text{ at } 1\text{ATA}} \quad [1]$$

$$R = \frac{(2)(0.79)}{1} = \frac{1.58}{1} = 1.58$$

In fact, there are apparently a number of critical supersaturation ratios for the various mathematical compartments, representing different tissues.

A person living at sea level and breathing atmospheric air will have a dissolved P_{N_2} of 573 mm Hg in all body tissues and fluids, assuming that P_B equals 760 mm Hg; P_{AO_2} equals 100 mm Hg; P_{ACO_2} equals 40 mm Hg; and P_{AH_2O} equals 47 mm Hg.

$$\begin{aligned} P_B \text{ (sea level)} &= 760 \text{ mm Hg} \\ &= \Sigma \text{ (partial pressures of all alveolar gases)} \\ &= P_{H_2O} \text{ (47 mm Hg)} + P_{CO_2} \text{ (40 mm Hg)} \\ &\quad + P_{O_2} \text{ (100 mm Hg)} + P_{N_2} \text{ (573 mm Hg)} \end{aligned}$$

If that person is rapidly decompressed to altitude, a state of supersaturation will be produced when an altitude is reached where the total P_B is less than 573 mm Hg, a condition that occurs at an altitude of 2,287 m (7,500 ft). Therefore, the altitude threshold above which an individual living at sea level would encounter supersaturation upon rapid decompression is 2,287 m (7,500 ft).

The lowest altitude where a sea-level acclimatized person may encounter symptoms of DCS may be lower than 3,962 m (13,000 ft) (46). However, recent data revealed a 5% threshold at 5,944 m (19,500 ft) (47) using a probit analysis of more than 120 zero-prebreathe, 4-hour exposures with mild exercise to generate an onset curve showing less than 0.001% DCS at 13,000 or below. The degree of supersaturation at 5,489 m (18,000 ft) can be expressed as a ratio, as follows:

$$R = P_{N_2} \Big/ P_B \qquad [2]$$

If the tissue P_{N_2} equals 573 mm Hg and P_B equals 372 mm Hg, then R equals 573/372, or 1.54. This value approaches the critical supersaturation ratio expressed by Haldane. The incidence of altitude DCS reaches 50% by 7,010 m (23,000 ft) with zero prebreathe and mild exercise at altitude (47).

Symptoms can occur at much lower altitudes when "flying after diving" or "diving at altitude and driving to higher altitude" (diving in mountain lakes). Many cases of DCS have been documented in divers who fly too soon after surfacing. Altitudes as low as 1,524 to 2,287 m (5,000 to 7,500 ft) may be all that is necessary to induce bubble formation in a diver who has made a safe decompression to the surface. The problem involves the higher tissue P_{N_2} that exists after diving. The Undersea and Hyperbaric Medical Society's recommended surface interval between diving and flying ranges from 12 to 24 hours depending on the type and frequency of diving (48).

Factors Influencing Bubble Growth

Upon decompression to altitude, the factors causing a bubble to grow are as follows:

1. Boyle's law ($P_1V_1 = P_2V_2$) expansion due to reduced pressure
2. Entrance of nitrogen from tissues in the state of supersaturation
3. Entrance of O_2 and CO_2 (negligible effect during decompression from hyperbaric exposures, significant in hypobaric exposures)

Boyle's Law Effects

Once a bubble is formed, its size will increase if the total pressure is decreased (Boyle's law: $P_1V_1 = P_2V_2$). During hyperbaric therapy, bubble size is reduced during compression. The surface tension of a bubble is inversely related to bubble size and opposes bubble growth. Therefore, as total pressure within the bubble is increased, the surface tension opposing bubble growth also is increased. Once a critically small bubble size is achieved, the surface tension is so high that the bubble can no longer exist. The bubble collapses, and its gases are dissolved (44,49).

Gaseous Composition

Nitrogen, or another inert gas, is generally considered to be the primary gas involved in symptomatic bubbles. If nitrogen were the only gas initially present in the newly formed bubble, an immediate gradient would be established for the diffusion of other gases into the bubble. Hence, a bubble will quickly have a gaseous composition identical to the gaseous composition present in the surrounding tissues or fluids. When bubbles are produced upon decompression from hyperbaric conditions, gases other than nitrogen represent only a small percentage of the total gas composition of the bubble. Exposure to a hypobaric environment decreases the partial pressures of all gases including nitrogen. The partial pressures of O_2 and CO_2 at the tissue level are close to independent from hypobaric or hyperbaric conditions because appropriate levels are a prerequisite for life. If we assume that a bubble were to be present at sea level (1 ATA) with O_2 and CO_2 representing 6%, respectively, of its total volume and pressure and we decompress to an altitude of 5,487 m (18,000 ft, 1/2 ATA), then O_2 and CO_2 would each account for 12% (together 24%) of the total volume and pressure of the bubble. If the decompression were instantaneous then O_2 and CO_2 would each account for 6% of the bubble volume, but the partial pressure would be half of the sea level partial pressures, which would cause an immediate influx of O_2 and CO_2 into the bubble accounting for 12% growth in bubble volume in this example. This example (45) illustrates the importance of the metabolic gases O_2 and CO_2 in hypobaric exposures; at this point it is also valuable to remember the important contribution of water vapor to bubble formation and gas behavior in general in a hypobaric environment (Figure 3-9B), especially as we approach water vapor pressure (47 mm Hg) and, therefore Armstrong's line (zone) at 63,000 ft.

Hydrostatic Pressure

The tendency for gases to leave solution and enlarge a seed bubble can be expressed by the following equation introduced by Harvey in 1944 (50):

$$\Delta P = t - P_{ab} \qquad [3]$$

where ΔP is the differential pressure or tendency for the gas to leave the liquid phase, t is the total tension of the gas in the medium, and P_{ab} is the absolute pressure (i.e., the total P_B on the body plus the hydrostatic pressure).

Within an artery at sea level, t equals 760 mm Hg. The absolute pressure, P_{ab}, is 760 mm Hg plus the mean arterial blood pressure (100 mm Hg), or 860 mm Hg. Therefore,

$$\Delta P = 760 \text{ mm Hg} - (760 \text{ mm Hg} + 100 \text{ mm Hg})$$
$$\Delta P = -100 \text{ mm Hg} \quad [4]$$

When the value of ΔP is negative, there is no tendency toward bubble formation or growth. If the value for ΔP becomes zero or positive, bubble formation or growth is likely to occur.

Within a great vein at sea level, P_{O_2} equals 40 mm Hg, P_{CO_2} equals 46 mm Hg, and P_{H_2O} equals 47 mm Hg; therefore, t equals 706 mm Hg and P_{N_2} is 573 mm Hg. Absolute pressure, P_{ab}, is 760 mm Hg plus the mean venous pressure (which in the great veins in the chest may be 0 mm Hg). Therefore,

$$\Delta P = 706 \text{ mm Hg} - (760 \text{ mm Hg} + 0 \text{ mm Hg})$$
$$\Delta P = -54 \text{ mm Hg} \quad [5]$$

By suddenly exposing a person to an altitude of 5,490 m (18,000 ft) without time for equilibration at the new pressure, venous ΔP would have a large positive value:

$$\Delta P = 706 \text{ mm Hg} - (380 \text{ mm Hg} + 0 \text{ mm Hg})$$
$$\Delta P = +326 \text{ mm Hg} \quad [6]$$

The value for t in the earlier equation can also be increased in local areas by high levels of CO_2 production. Hence, in muscular exercise, a high local P_{CO_2} associated with a reduction in P_B causes higher positive values of ΔP than with a reduction in P_B alone. It is important to appreciate that this is a highly localized process, unless the exercise is at anaerobic levels; situations of this nature are not likely to occur for more than a few minutes in the operational aerospace environment due to the ensuing fatigue.

Hydrostatic pressure is, therefore, considered to be a force opposing bubble formation or bubble growth and includes not only blood pressure and cerebrospinal fluid pressure but also local tissue pressure (turgor), which varies directly with blood flow.

Influence of Tissue Perfusion and Diffusion

The rate of inert gas washout from tissues is dependent on perfusion; therefore, factors that alter tissue perfusion influence inert gas washout. Studies in the hypobaric environment have shown that exercise before exposure reduces the risk of DCS while prebreathing oxygen (DCS incidence decreased from 90% to 20%) (51). The putative mechanism for these effects is the increase in cardiac output with increased peripheral circulation as well as vascular volume shifts to the chest during immersion. Negative pressure breathing has similar effects to immersion with increases in cardiac output and increased inert gas washout (52). Changes in body position do have similar influence on inert gas washout; supine position has similar effects to immersion compared to the erect body position. Effects of temperature—in the context of tissue perfusion—are mediated by changes in vascular tone, as warm temperature will result in vasodilatation and enhanced inert gas washout, whereas lowering of the temperature results in vasoconstriction and decreased inert gas washout.

Pathophysiology of Bubbles

The presence of bubbles in tissues has direct and indirect effects. The location of bubbles is important in this context; extravascular bubbles can cause local tissue distortion, dysfunction, and possibly local ischemic changes. The painful sensations of joint pain are thought to be related to compressive effects on periarticular, peripheral nerve fibers. Intravascular bubbles are of lesser importance in the context of hypobaric DCS unlike their role in diving DCS, they may—depending on their location within the vasculature and the tissue—cause symptoms due to local relative hypoperfusion. The indirect effects of bubbles are more complex in nature; the interaction of cells (blood, tissue, endothelium) with the bubble surface leads to the release of mediators, which in turn may influence chemotaxis for leucocytes (polymorphonuclear neutrophils) with subsequent generation of oxygen radicals, complement activation, activation of the intrinsic coagulation pathway, generation of arachidonic acid metabolites, release of endothelium-derived mediators to name just a few. The modulation of these tissue reactions depends furthermore on the target tissues, the bubble load (dose–response), local factors such as degree of ischemia, collateral circulation, reperfusion injury, and environmental factors, for example, hypoxia, exercise, temperature, and rapidity of ambient pressure change (44,49,53).

The putative fate of bubbles formed during decompression is summarized in Figure 3-4. It is important to emphasize that our knowledge is far from complete and that the extravascular bubble dynamics are of more relevance to altitude DCS compared to the intravascular bubbles of diving DCS.

Target Organs of Bubbles Created during Decompressive Stress

Lungs

VGE results in a dose-dependent increase of pulmonary artery pressure and subsequent increase in pulmonary vascular resistance (54). These changes can be attributed to mechanical obstruction of the pulmonary vascular bed and vasoconstriction; hypobaric exposures of greater than 24,000 ft (7,315 m) did not result in appreciable increases in pulmonary arterial pressures (55). In cases with large gas loads that overwhelm the capacity of the pulmonary circulation filter, the embolization of the pulmonary vascular bed results in ventilation–perfusion mismatching leading to decreased peripheral arterial O_2 saturation and decreased end-tidal CO_2 levels (56).

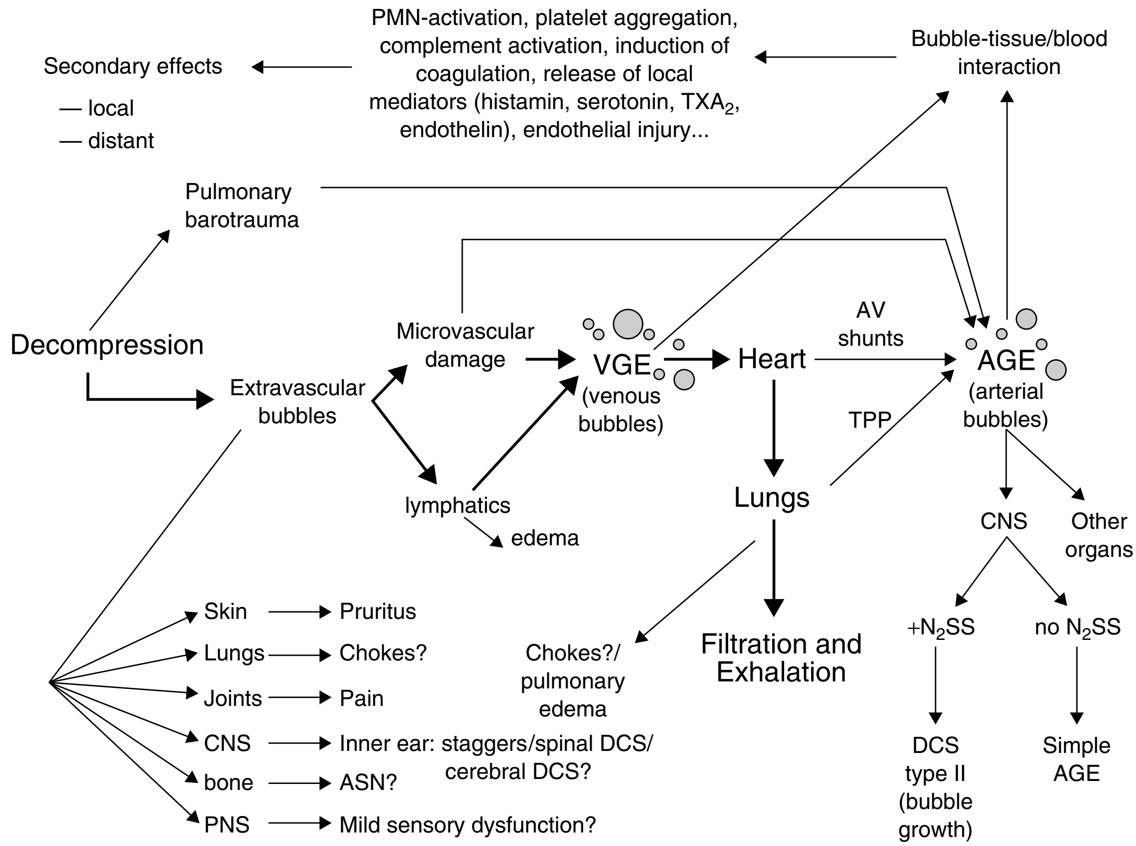


FIGURE 3-4 Synopsis of the putative pathophysiological pathways of bubbles in decompression sickness (DCS), *bold arrows* indicate the major physiological pathway for elimination of inert gas, question marks indicate lack of scientific literature proving the postulated relationship.
PMN, neutrophilic leucocytes TXA_2, thromboxane A_2; VGE, venous gas emboli; AV, arteriovenous; AGE, arterial gas emboli; TPP, transpulmonary passage; CNS, central nervous system; N_2SS, nitrogen supersaturation; DCS type II, serious neurologic (cerebral) decompression sickness; ASN, aseptic bone necrosis; PNS, peripheral nervous system.

In experimental animal studies, large doses of VGE can impair cardiac output and arterial blood pressure (likely due to right ventricular failure and decreased myocardial perfusion). Left ventricular end-diastolic pressure is typically not altered. In addition to the hemodynamic effects of pulmonary VGE, there is evidence of bronchoconstriction and substernal discomfort as well as paroxysmal coughing and permeability changes in the pulmonary vascular bed leading to fluid shifts and pulmonary congestion/edema (57–59).

The lungs are a very efficient filter mechanism that removes VGE from the circulation. This mechanism can be overloaded possibly resulting in spillover of venous bubbles into the arterial circulation (transpulmonary passage of bubbles) (55). Venous bubbles that undergo transpulmonary passage become arterialized and hence can pose the risk of AGE (44,49,55).

Heart

Morphologic abnormalities or variations of the cardiac anatomy resulting in opportunities for shunting between the right and left side of the heart [such as large atrial septal defects (ASDs) or a patent foramen ovale (PFO)] can result in arterialization of venous bubbles and may theoretically represent an increased risk for AGE (44,49,55).

Central Nervous System

When bubbles reach the cerebral vasculature and result in an occlusion to blood flow, the vessels react with a temporary vasoconstriction followed by a marked dilation of the downstream microcirculation and venules. Experimental evidence exists for transport of cerebral gas bubbles through the capillaries into the venous bed. This fact has been offered as an explanation for the fact that approximately 60% of divers with cerebral DCS recover before recompression therapy is initiated; furthermore, this has led to the speculation that neurologic defects following cerebral gas embolism are likely due to secondary changes in the microvasculature (endothelium) as opposed to the transient obstruction to blood flow by the bubbles. Autochthonous bubble formation within the white matter of the spinal cord has been implicated in the pathogenesis of spinal cord DCS as well as epidural vein bubbles and AGE. Experimental studies on cats have shown that severe cardiac arrhythmias and hypertension can be induced by injection of air into the vertebral arteries. This has led to the conclusion that the cardiac dysfunction in DCS may be closely linked to cerebral embolism (53).

Blood

The interaction of blood components and endothelium with the bubble surface results in a cascade of changes (44,60) Most of the data in this context relate to and emanate from diving-related DCS as opposed to altitude DCS. Thrombocyte aggregation with a low platelet count has been reported. Neutrophils sequester in the pulmonary vascular bed with activation of the intrinsic coagulation pathway, presumably by activation of the contact system activator Hageman factor, and endothelial damage through release of oxygen radicals. Platelets and leucocytes have been shown by electron microscopy to adhere to circulating bubbles. In addition, activation of the complement system takes place; its contribution to the pathophysiologic sequence in DCS however is not clear (49,61).

Human studies in diving DCS have shown increases in hematocrit (hemoconcentration) and decreased platelet count in serious cases of DCS, suggesting microvascular damage with loss of plasma volume (61,62).

Incidence Data

The incidence of altitude DCS in the altitude chamber training environment varies among facilities and countries; European military training facilities (UK) have reported five cases of DCS type I (pain only) over a 5-year period (1983–1987) among 12,000 exposures to 7,622 m (25,000 ft) equal to a rate of 0.41 per 1,000 exposures (62). Data regarding the incidence of DCS in inside observers in the United Kingdom has not been formally reported; anecdotal evidence corroborates its existence (62,63). The United States Navy (USN) reported 41 cases in 20,778 exposures to 7,622 m (25,000 ft) from January 1996 to October 2000 (63). This equals a rate of 2 per 1,000 exposures; inside observers experienced a rate of 0.18% and trainees 0.21%. The experience of U.S. Army for the years 1984 to 1989 was 42 cases of DCS in 21,498 exposures (0.195 per 1,000 exposures; inside observer to student rate ratio was 3.17) (64). The USAF reported for 1985 to 1987 (exposures to 7,622 m (25,000 ft) 34 cases among 80,048 exposures, which translates into an incidence rate of 0.042% (0.4 per 1,000 exposures) (65).

The flight incidence for the USAF during the period 1980 to 1990 was 49 DCS incidents, which translates to a DCS mishap rate of approximately 0.2 to 0.3 per 100,000 flying hours (66).

For a discussion regarding EVA risk in space operations see Chapter 10.

From the operational perspective of the aviator, DCS does not pose a significant risk for any single mission in view of the above numbers; it is a rare event and very serious outcomes (death, disability) are exceptionally rare (one fatality in aviation since 1959) (67). In the past, the threat to the aviator was the reporting process itself because the fact that DCS was experienced did result in grounding of a capable operator. This aspect probably did introduce reporting bias into the reported incidence figures (operational underreporting). To reduce a possible source of reporting bias, negative consequences of reporting should be avoided and detailed education on the possible signs and symptoms of DCS should be given to aircrew (recognition of a symptom is based on the knowledge of a symptom). Reporting of DCS symptoms has become a physiologic incident without punitive ramifications for the flying career of the aviator and as a result data from extreme altitude operation environments (e.g., U2 surveillance aircraft) started to emerge (68). A similar situation in the operational environment was encountered with G-induced loss of consciousness (G-LOC). There was no obvious G-LOC problem apparent among military aviators until a targeted survey, without penalty for reporting incidents, was done and only then the real incidence of G-LOC emerged.

Factors Thought to Affect Decompressive Sickness

Attempts have been made to correlate the incidence of both diving-induced and altitude-induced DCS with various environmental and physiological factors. A review of the existing data documenting the presence or absence of association of these factors with altitude DCS is summarized in the next sections.

Altitude Attained

With increasing altitude, the incidence of DCS increases, as does the ratio of severe to mild cases. The severity of the cases will increase with increasing altitude (47,69).

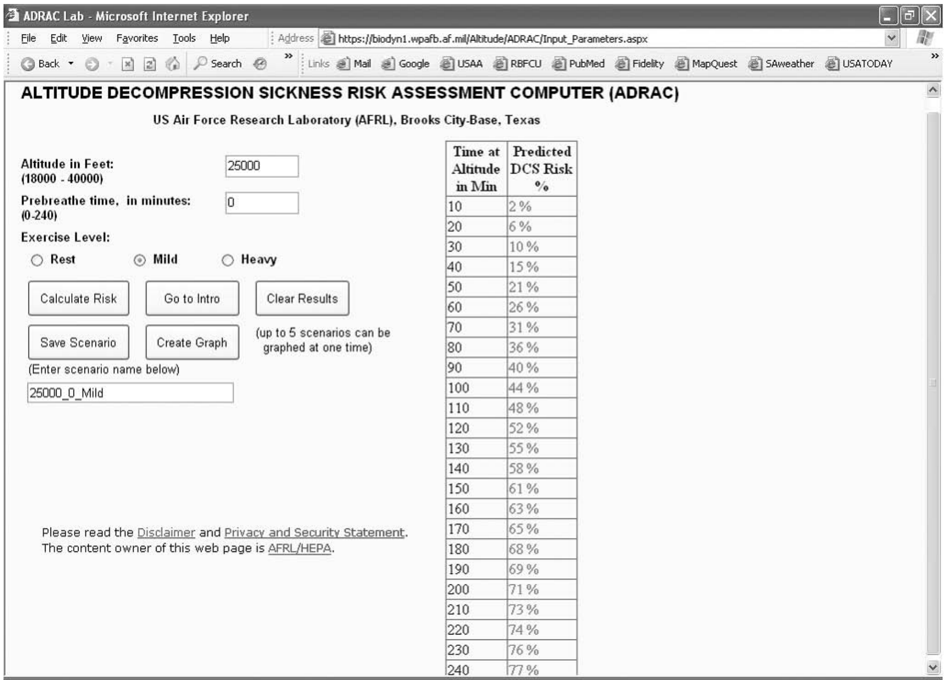
In a review of 145 cases of altitude-induced DCS necessitating treatment, Davis et al. (70) reported that 13% of these cases occurred with altitude exposures of 7,622 m (25,000 ft) or below and 79% occurred with exposures of 9,146 m (30,000 ft) or greater.

Duration of Exposure

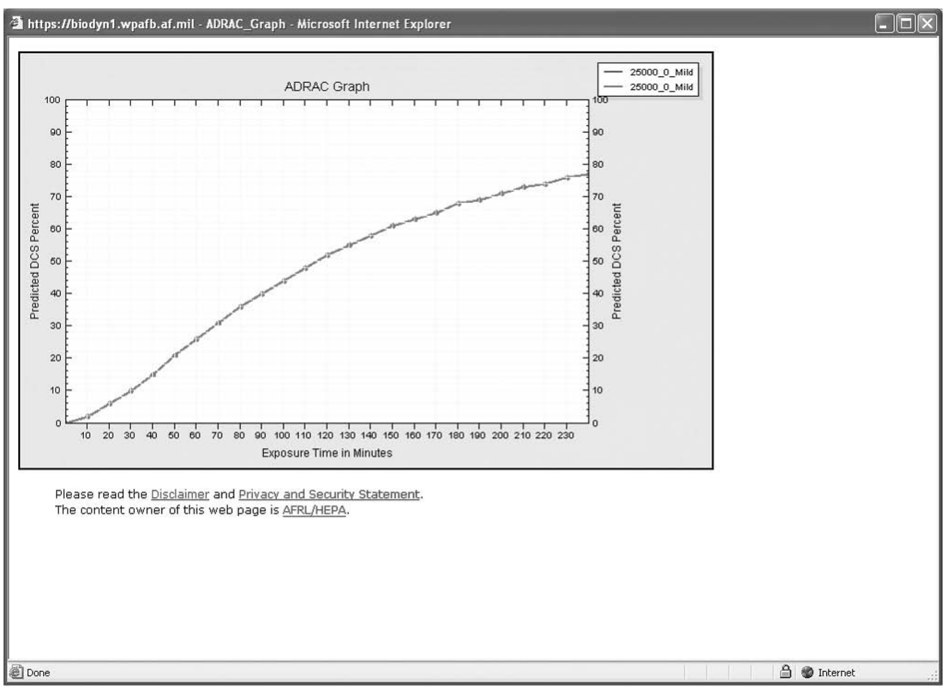
At all altitudes above 5,488 m (18,000 ft), the longer the duration of exposure, the greater the incidence with DCS occurring after 5 hours of exposure to 25,000 and 27,500 ft even after 1 hour of prebreathes. Some subjects, however, will not develop DCS at a given altitude (individual susceptibility), even after extended periods of time (71).

Combination of Environmental Factors to Predict Decompression Sickness Risk

Pilmanis et al. (72) developed an Altitude Decompression Sickness Risk Assessment Computer (ADRAC) model that uses altitude, time at altitude, level of activity, and preoxygenation time for various time, exposure, and preoxygenation scenarios (Figures 3-5A, 3-5B & 3-6).



A



B

FIGURE 3-5 **A:** Altitude Decompression Sickness Risk Assessment Computer (ADRAC) prediction of DCS risk at 25,000 ft with no pre-breathe and mild exercise. **B:** ADRAC graph of DCS risk at 25,000 ft with no prebreathe and mild exercise.

Previous Exposures to Altitude

Each successive altitude exposure to 25,000 ft does lead to increasing amounts of eliminated inert gas (especially if the breathing gas is 100% oxygen) and therefore results in decreased DCS and VGE incidence compared to a single continuous exposure (73).

The series of cases reported by Davis et al. (70) illustrates the increased incidence of DCS in inside observers (who continuously ambulate in the altitude chamber to monitor their trainees during the exposure). The key DCS risk factor in the aforementioned case series is the physical activity of the inside observer and not the actual repeat exposure itself. Recent experience from the USN suggests that the incidence among students and inside observers may be identical provided that both groups undergo diligent preoxygenation before altitude exposure (74).

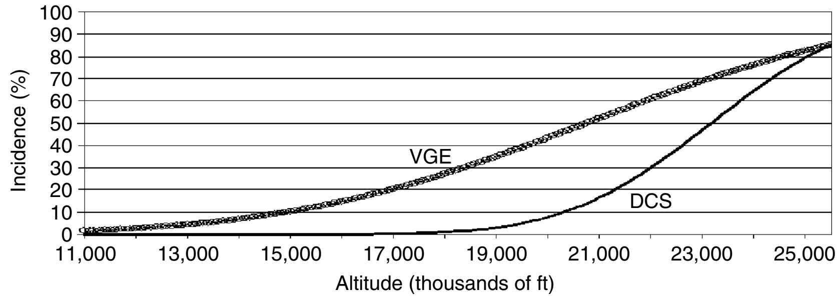


FIGURE 3-6 Zero-preoxygenation altitude threshold curves for decompressive sickness (DCS) and venous gas emboli (VGE).

Flying Following Diving

If an individual breathes a gas at pressures greater than sea level before altitude exposure, his/her susceptibility to DCS will significantly increase. Retrospective case reviews as well as prospective animal and human investigations have resulted in a number of recommendations by various agencies as to the sea level surface interval necessary to safely fly after diving. Recent studies by Pollock et al. showed no apparent increase in DCS risk after dry resting 60 fsw/60 min air dives followed at least 12 hours later by a resting 25,000 ft 3-hour flight while on 100% oxygen (75). The Undersea and Hyperbaric Medical Society reviewed this material and recommended the following (48):
Dive Schedule Minimum Surface Interval

1. No-decompression dives
   a. Less than 2 hours accumulated dive time in the 48 hours preceding surfacing from the last dive wait 12 hours
   b. Multiday, unlimited diving wait 24 hours
2. Dives requiring decompression stops (but not including saturation dives) wait 24 to 48 hours

Saturation diving presents complex problems and is beyond the scope of this chapter. The interested reader is referred to the specialized literature on the subject (see list of **Recommended Reading** in reference section).

Age

Recent work (47) showed increased DCS risk with age in males and decreased DCS risk with age in females, with all subjects showing no difference due to the opposite effects of age based on gender. Height had no effect. Factors that did correlate with increased risk included higher body mass index and lower physical fitness.

Gender

Retrospective studies indicated initially that the incidence of DCS in female subjects is significantly higher than in males (70,76,77). Prospective studies have not revealed any significant differences between male and female for DCS symptoms (47,78). Of note, women using hormonal contraception showed significantly higher DCS susceptibility compared to those not using hormonal contraception during the latter 2 weeks of the menstrual cycle (47).

Exercise

The association between physical exertion at altitude and DCS has been well established. During World War II, altitude chambers were used to select out bends-prone individuals from aircrews. The subjects were taken to an altitude of 12,195 m (40,000 ft) and exercised at altitude until half of them developed bends. The remaining bends-resistant subjects were assigned to high-altitude, unpressurized bomber missions. The effect of exercise on the incidence of DCS is equivalent to increasing the exposure altitude 915 to 1,524 m (3,000 to 5,000 ft). Recent studies on the effect of mild versus strenuous exercise at 10,671 m (35,000 ft) have shown that both significantly increase DCS incidence (79).

Exercise during oxygen prebreathe has been shown to significantly decrease DCS risk by increasing inert gas washout (increased perfusion) (51,80–82). The method has been used successfully to provide additional protection for high-altitude reconnaissance pilots (83) and during preparation for EVA from the ISS (84).

Injury

No convincing evidence exists to associate previous injury with DCS. On the basis of theoretic considerations, however, it is thought that during the acute stages of injury a joint may have increased susceptibility to DCS pain because of perfusion changes associated with the injury and/or healing mechanisms.

Body Build

For a long time, a basic tenet of diving and aerospace medicine has been that obesity increases the susceptibility to DCS; data from work from the United States Air Force School of Aerospace Medicine (USAFSAM) tended to confirm these historic tenets showing an increased DCS risk with increased body mass index (47,85).

Other Factors

Temperature

No good correlation exists between the frequency of DCS and the ambient temperature, with the exception of work done by Balldin in the context of warm water immersion and its effects on increased nitrogen washout (52).

Hypoxia

There is significant overlap between the symptoms of DCS and hypoxia. Hence, careful distinction between the two entities needs to be made. There is anecdotal evidence suggesting an association of hypoxia and DCS (86). The few published studies suggest no effect of hypoxia (87–89).

Acid–Base Balance

Elevated P_{CO_2} has been associated with the incidence of severe DCS in several studies (39,90,91). Deliberate hyperventilation at altitude has been found to decrease the pain associated with DCS. The question arises as to whether the contribution of elevated P_{CO_2} affects bubble growth or primary modulation of pain perception by altered acid–base balance.

Dehydration

Individuals with an overall high average daily fluid intake were found to be less susceptible to DCS than a comparable group of individuals with a restricted fluid intake over 2 weeks. These findings were corroborated in three separate studies (92–94).

Effects of Microgravity

Under microgravity conditions, fluid shifts (increase in central blood volume) occur, which may have an effect on pulmonary perfusion and modify nitrogen washout dynamics from tissues. Static unloading may produce fewer bubble nuclei. These effects constitute physiological inference without controlled studies under microgravity to corroborate them at this point. To date, there has not been a confirmed DCS event during EVA in the United States and international space programs. Further information will accrue from the medical investigation programs on the ISS. The effect of ambulatory (walking during exposure) versus nonambulatory exposures with the same metabolic cost of activity while decompressed yielded no difference in DCS risk (95), or in total joint pain DCS (96). These papers concluded that walking under 1-G conditions during exposure would not produce DCS levels higher than during supine exposures emulating weightlessness. However, the distribution of joint pain was different with the upper body developing more DCS than the lower body during nonambulatory exposures with the reverse true during ambulatory exposures (96).

Patent Foramen Ovale

This is an area of current investigation and controversy due to its potential impact on selection of personnel for work in environments that may put the individual at risk for DCS. Hypothetically, a PFO could allow arterialization of venous gas bubbles by transforaminal passage of bubbles from the right atrium to the left atrium and make them a possible risk factor for cerebral DCS/AGE (97).

Longitudinal data to define the risks in hyper- or hypobaric environments are not available in the literature. A meta-analysis of the relationship between DCS and PFO in diving showed a risk ratio of 2.52 for PFO, with an incidence of 5.7 cases of type II DCS per 10,000 dives (98). Clinically silent cerebral lesions [magnetic resonance imaging (MRI), T2 weighted images] in divers with hemodynamically significant PFO have been described (99); the clinical significance of this finding is unclear at this point in time.

The data in the altitude DCS setting are sparse at this point; a clear relationship between altitude DCS and PFO has yet to be firmly established. No link between PFO and DCS (41) was found in the six cases of left ventricular gas emboli (LVGE) observed throughout 1,075 subject exposures where echo-imaging of the right and left heart was used. Of the five subjects with LVGE who were evaluated for PFO, three were negative by transthoracic echocardiography (TTE) or transesophageal contrast echocardiography (TEE), one was positive for PFO by TEE, and one displayed a sinus venosus by TEE. It is important to keep in mind that a significant proportion of asymptomatic, healthy adults do have a PFO (prevalence 27.3%) (100). The published literature does not allow the conclusion that subjects should be disqualified from hypobaric duties based on the presence of a PFO alone. The presence of a history of events suggestive of a right to left shunt should trigger further appropriate testing as clinically indicated.

Miscellaneous Factors

Lower physical fitness was shown to be related to increased DCS risk (47,85) in both females and males ($p < 0.05$); the least fit (lowest third of VO_2) 254 versus the most fit (highest third VO_2) 254 subjects whose VO_2 were evaluated. A later analysis with a larger sample size showed a significant relationship between lower physical fitness and increased susceptibility to DCS ($p < 004$).

Preventive Measures

Protection against DCS is based on controlling the tissue nitrogen-to-ambient pressure ratio (P_{N2}/P_B). When an inert gas, such as nitrogen, is breathed, the tension of the gas dissolved in tissue fluids increases until equilibrium with the partial pressure of the gas in the respired medium is reached. With pressure reduction (decompression), supersaturation can occur. Some degree of supersaturation can be tolerated. The critical P_{N2}/P_B ratio differs for each body tissue. When the safe limits of decompression are exceeded, gas separates from solution in the blood and other tissues. This process is the initiating event for DCS, although there is considerable variability between and among individuals as to whether or not DCS results from any event causing bubble formation. For diving, safe decompression limits vary with time and the depth of the dive and are published as decompression tables in a variety of diving manuals, one of which is the USN Diving Manual (101).

The aviator is protected from DCS in two ways, aircraft pressurization and denitrogenation (102). Aircraft pressurization is a method of maintaining the aircraft cabin pressure and, therefore, the physiologic altitude to which the aviator is exposed, at a considerably lower PA than the actual altitude at which the aircraft is flying. With adequate aircraft pressurization, the individual is not exposed to reduced P_B where bubbles can form.

Denitrogenation is a method by which one breathes 100% O_2 for the purpose of eliminating N_2 from the body before going to altitude. This method is used to protect the individual who must ascend to high altitudes that can produce DCS. With 100% O_2 breathing, O_2 replaces other tissue-dissolved gases, including N_2. Therefore, the amount of N_2 in each body tissue is reduced before ambient pressure reduction occurs. The P_{N2}/P_B ratio is reduced, because the value for P_{N2} is reduced, thereby decreasing the risk.

For example, an aviator rapidly ascends from sea level ($P_B = 760$ mm Hg) to 5,488 m (18,000 ft) ($P_B =$ 380 mm Hg). The aircraft pressurization system maintains pressure in the cabin at 2,439 m (8,000 ft) ($P_B = 565$ mm Hg). Assuming that all tissues are saturated at sea level ($P_{N2} =$ 573 mm Hg) and that offgassing occurring during the rapid ascent is insignificant, the P_{N2}/P_B ratio would be 1.01:

$$\frac{P_{N_2}}{P_B} = \frac{573 \text{ mm Hg}}{565 \text{ mm Hg}} = 1.01 \qquad [7]$$

If the aircraft were not pressurized the P_{N2}/P_B ratio would be 1.51:

$$\frac{P_{N_2}}{P_B} = \frac{573 \text{ mm Hg}}{380 \text{ mm Hg}} = 1.51 \qquad [8]$$

If unpressurized flight occurred to 9,140 m (30,000 ft) ($P_B = 226$ mm Hg) the P_{N2}/P_B ratio would be 2.54:

$$\frac{P_{N_2}}{P_B} = \frac{573 \text{ mm Hg}}{226 \text{ mm Hg}} = 2.54 \qquad [9]$$

If before unpressurized flight to 9,146 m (30,000 ft) the aviator had denitrogenated at sea level for a long period of time such that one half of the total N_2 was eliminated from his body, the P_{N2}/P_B ratio would be 1.27:

$$\frac{P_{N_2}}{P_B} = \frac{287 \text{ mm Hg}}{226 \text{ mm Hg}} = 1.27 \qquad [10]$$

The process of denitrogenation is very effective in eliminating N_2 from the body. When 100% O_2 is breathed using a tightly fitted mask, an alveolar N_2 pressure of nearly zero is established and a marked pressure differential (~573 mm Hg) between the alveoli and body tissues results. N_2 rapidly diffuses from the tissues into the blood, where it is transported to the lung and is exhaled. The amount of N_2 eliminated depends on time and tissue perfusion.

Figure 3-7 shows the total amount of N_2 washed out of the body by denitrogenation. Assuming that the average person contains 1,200 cm^3 of dissolved N_2, slightly more than 350 cm^3 can be eliminated by prebreathing 100% O_2 for 30 minutes. Denitrogenation before initiating ascent to altitude significantly reduces the incidence of altitude DCS as does the operational use of inflight denitrogenation with 100% O_2 at or below 4,878 m (16,000 ft) (103). Once begun, denitrogenation should ideally not be interrupted although recent evidence indicates that breaks in prebreathe, up to 60 minutes in the middle of a 1-hour prebreathe, may not result in increased DCS risk (104).

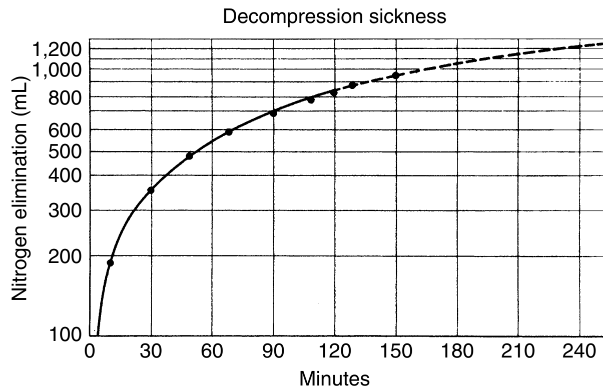


FIGURE 3-7 Denitrogenation curve while breathing 100% oxygen.

Denitrogenation eliminates nitrogen from various tissues at different rates. These rates are dependent on the solubility of nitrogen in specific tissues but, more importantly, also on the circulatory perfusion of the tissues. Therefore, all body tissues come into equilibrium with each other and with respired gas at different times. As a practical matter, then, with altitude exposure (pressure reduction), the P_{N2}/P_B ratio of certain tissues may exceed the critical value for bubble formation, whereas the P_{N2}/P_B ratio of other tissues remains within a safe range. This fact may partially explain why signs and symptoms of DCS occur at characteristic locations in the body.

MANIFESTATIONS OF DECOMPRESSION SICKNESS

In DCS, bubbles can form in all parts of the body. Various target organs, however, seem to be affected most readily, and the effects on these anatomic locations account for the signs and symptoms seen. In this section, the clinical manifestations of bubble formation and the classic syndromes of DCS will be described.

Classification

DCS symptoms have been categorized as type I (pain only) and type II (serious) since introduction of the nomenclature in 1960 by Golding et al. (105). This categorization was created to separate the symptoms into groups based on their response to treatment during or after decompression from caisson work on the Dartford Tunnel in England. This system was somewhat analogous to the four-table treatment scenarios used at that time by the USN as described by Donnell and Norton (106). The four hyperbaric Treatment Tables (I–IV; I-A, and II-A without oxygen available) involved treating increasing symptom severity with more aggressive hyperbaric profiles. The Golding classification in type I and type II DCS has significant clinical shortcomings in the context of hypobaric DCS. Type I and type II DCS do not represent mutually exclusive categories; therefore, it is possible that a subject may have features of both concomitantly. Furthermore the static classification does not take into account that DCS is a dynamic process, therefore, a patient may transition from a type I DCS class to a type II DCS over time.

The dynamic nature of the condition should be documented by repeat assessments of the clinical examination (especially neurologic examination), response to treatment, progression, relapse of symptoms, time to onset of symptoms (latency), time to start of recompression therapy, as well as results of any investigations. The adherence to DCS examination/assessment checklists may prove valuable to maximize reproducibility of data collection and subsequent analysis.

The USN uses the type I and type II categories of DCS for the Master Diver to determine treatment of diving DCS. The Master Diver provides hyperbaric oxygen (HBO) treatment as needed for USN divers in the absence of a physician on-site (a telephone consultation with the diving physician is part of the process), creating a need for clear guidelines regarding treatment. USAF physicians determine treatment for altitude DCS based on the symptoms and their severity. An accurate description of a case of altitude DCS involves stating the dynamic evolution of each symptom (107) (Table 3-5).

- Spontaneously resolving
- Static
- Relapsing
- Progressive

Each symptom should be stated with the time interval from its onset to the commencement of treatment. Progressive, limb-pain DCS occurring 1 hour before commencement of treatment would provide essential information in determining treatment, unlike "type I DCS." The timeline of any relapsing or progressive symptoms should be further described to include an indication of change and level of intensity. In addition, the response to recompression should be indicated (complete recovery, incomplete recovery, or none) to guide any further treatment options. The careful documentation of pertinent results of any investigations and tests and their respective timing is also of importance to allow for additional parameters for decision making in the context of treatment (Table 3-6).

Decompression Sickness Pain

Altitude DCS pain is seen in 65% to 80% of the cases of altitude-induced DCS (108–110). It tends to be localized in and around the large joints of the body. Sometimes smaller joints, such as interphalangeal areas, may be affected, particularly if these joints underwent significant active motion during altitude exposure.

DCS pain is deep and aching in character and ranges from very mild (joint awareness) to so severe that the patient does not wish to move the affected joint. Active and passive movement of the joint tends to aggravate the discomfort,

TABLE 3-5

Decompressive Stress—Classification and Clinical Consideration

Key Clinical Descriptors	*Affected Organ/Tissue*	*Signs and Symptoms*
Evolution of symptoms: spontaneous resolution/static/relapsing/progressive	Joints, pain only	Mild discomfort at the beginning (ache, "niggles"), progressing to severe, dull, deep, throbbing pain; no single, tender points; relieved by external compression
Response to therapeutic interventions: Pressure/oxygen	Cutaneous and lymphatic manifestations	Transient pruritus (especially trunk, ears, wrists, hands) colloquially known as *creeps*, possibly associated with a scarlatiniform rash; truncal *peau d'orange*,
Meticulous documentation of timeline		Cutis marmorata: marbled/mottled skin lesions [confluent rings of pallor surrounded by cyanosis (blanches to touch)]
Vital signs: heart rate, respiratory rate, degree of pain, measure of oxygenation	Cardiovascular	Circulatory collapse after preceding severe bends, chokes, or other neurologic symptoms
		Rhythm disturbances (e.g., first degreeAV-block)
	Pulmonary ("chokes")	1. Substernal pain (worse with inspiration) 2. Dyspnea (with or without cyanosis) 3. Dry, nonproductive cough (paroxysms after deep inspiration)
Careful neurologic examination so as to avoid subtle progressive signs	Neurologic: cerebrum and cranial nerves	Altered mental status (impaired memory, judgment, aphasias), frank delirium, fatigue, visual disturbances (sctomas, diplopia, blurred vision), personality changes, loss of consciousness, headache; vertigo, nausea, vomitus, tinnitus
	Cerebellum	Abnormal Romberg test, abnormal gait
	Spinal cord	Sensory/motor deficits, abnormal tendon-reflexes, frank paralysis/paresis
	Vestibular ("staggers")	Vertigo, nausea, vomiting, occasional nystagmus

(Francis J. The classification of decompression illness. Hypobaric Decompression Sickness. San Antonio, Brooks Air Force Base, Texas: Aerospace Medical Association and Undersea & Hyperbaric Medicine Society, 1990. Published June 1992; the table is not part of the old reference, rather a summary table and created by the author (Stepanek).)

TABLE 3-6

Management of Altitude Decompression Sickness

Carefully Assess DCS Symptoms

1. Joint pain or skin symptoms only; A–D; not, 2
   A. Symptoms present in <2 hr?
      Surface level oxygen
         Worsen or fail to improve?
            Treatment Table 5
               Worsen or fail to improve?
                  Treatment Table 6
                     Worsen or fail to improve?
                        Consider extensions and tailing dives until resolution or until symptoms plateau
   B. Symptoms present in 2 to 6 hr?
      Treatment Table 5
         Worsen or fail to improve?
            Treatment Table 6
               Worsen or fail to improve?
                  Consider extensions and tailing dives until resolution or until symptoms plateau
   C. Symptoms present >6 hr?
      Treatment Table 6
         Worsen or fail to improve?
            Consider extensions and tailing dives until resolution or until symptoms plateau
   D. Symptoms present >36 hr?
      Reconsider diagnosis of DCS
2. Neurologic, pulmonary, or cardiac symptoms
   Treatment Table 6
      Worsen or fail to improve?
         Consider extensions or Treatment Table 6A and tailing dives until resolve or symptoms plateau

Courtesy of Hyperbaric Medicine Group at Brooks City Base, San Antonio, TX.

whereas local pressure, such as with an inflated blood pressure cuff, tends to relieve the pain temporarily, although other investigators (111) found the technique to be unreliable.

The pain may occur during the altitude exposure, on descent, shortly after descent, or, in rare cases, only become manifest many hours after descent. In nearly all cases, DCS pain occurring at altitude will be relieved by descent because of the increase in P_B. In rare cases, DCS pain relieved by returning to ground level will recur at ground level. In these cases, as well as those cases where pain is not relieved by descent, HBO therapy is the definitive form of treatment. It is important not to treat DCS pain with analgesics as its disappearance may serve as an indicator of the success of hyperbaric therapy.

Thoracoabdominal pain should not be classified as simple DCS pain, but rather as neurologic DCS likely due to spinal chord involvement and treated appropriately (112).

Chokes

The syndrome called *chokes* is rare in both diving and aviation, accounting for less than 4% of DCS cases (108,110) during research exposures. However, this condition may be a life-threatening disorder. The mechanism of chokes is multiple pulmonary gas emboli. The characteristic clinical picture consists of the triad of substernal chest pain, dyspnea, and a dry nonproductive cough, although only three cases of chokes with the full triad were found during a review of 2,525 exposures with 1,030 cases of DCS and 29 cases of chokes (108). Rudge has reviewed the USAF experience from 1966 to 1994 and found that the single most consistently present clinical sign in their series of 15 patients was substernal pain (113). In most cases, the pain is made worse on inhalation. Patients with chokes feel generally and severely ill. Altitude-induced chokes will invariably progress to collapse of the individual if the altitude is maintained. The aviator with chokes may need hyperbaric chamber therapy, although some may resolve during descent before or during ground level oxygen therapy (108).

Neurologic Decompression Sickness

Neurologic DCS presents a clinical picture with signs and symptoms referable to the nervous system. It has become apparent that one should probably limit the term neurologic DCS to those cases in which there is involvement of the CNS. Peripheral nerve involvement with mild paresthesia is commonly associated with altitude DCS and does not appear to increase the gravity of the disorder from a prognostic point of view unless it presents in a dermatomal pattern. CNS involvement, however, can herald significant and permanent neurologic deficits, particularly if aggressive and proper treatment is not instituted promptly.

CNS involvement occurs in 4% of cases of altitude DCS (109). It presents in one of two forms—spinal cord form or brain form. The spinal cord form is seen almost exclusively following diving and is extremely rare following altitude exposure. The brain form of the disorder is more commonly seen following altitude exposure and is uncommon but not rare following diving exposure. The reasons for the variance in the incidence of brain and spinal cord neurologic DCS in diving and altitude exposure have not been elucidated yet. The clinical manifestations of the two forms of this disorder will be discussed separately.

Spinal Cord Decompression Sickness

In many cases, the first symptom of spinal cord DCS is the insidious onset of numbness or paresthesia of the feet. The sensory deficit spreads upward, accompanied by an ascending weakness or paralysis to the level of the spinal lesion. Other cases begin with girdling abdominal or thoracic pain, which precedes the onset of sensory and motor deficits. Within 30 minutes of onset, the entire clinical picture of a partial or complete transverse spinal cord lesion may manifest.

The culprit lesions in spinal cord DCS have been well documented as bubbles formed in or embolized to the paraspinal venous plexus. Poorly collateralized segmental venous drainage of the spinal cord and normally sluggish blood flow through the paraspinal venous plexus can result quickly in mechanical blockage of venous drainage by bubbles and solid elements formed at the blood–bubble interface. This blockage, in turn, results in a congestive, or "red," infarct of the spinal cord (50). This is extremely rare in altitude DCS and may be found more frequently in diving DCS cases.

Brain Form of Decompression Sickness

In most cases, the clinical picture of a patient having the brain form of DCS is one of spotty sensory and motor signs and symptoms not attributable to a single brain locus. Headache, at times of a migrainous nature, is commonly present. Visual disturbances, consisting of scotomas, tunnel vision, diplopia, or blurring, are common. At times, extreme fatigue or personality changes that range from emotional lability to a significantly flattened affect are the presenting symptoms.

For the physician not acquainted with the clinical picture of multiple brain lesions, the diagnosis can be very difficult. A number of these patients have been misdiagnosed as hysterical and have progressed to vasomotor collapse because proper and immediate definitive treatment was not rendered.

Circulatory Manifestations

Generally, circulatory impairment is manifested as shock following the development of chokes or severe neurologic impairment (secondary collapse). Circulatory collapse without other symptoms preceding the development of shock (primary collapse) occurs rarely. The so-called post-decompression collapse following altitude exposure, with the shock state occurring after descent to the ground level, has been described as a separate type of circulatory impairment. It probably is not separate but rather represents delay in onset as sometimes seen with other types of altitude DCS.

Possible mechanisms of circulatory collapse include direct involvement of the vasomotor regulatory center or massive blood vessel endothelial damage by bubbles, with a subsequent loss of intravascular volume. Extreme hemoconcentration has been documented in many cases, with hematocrits up to 70% (61).

Circulatory collapse is marked by its lack of response to fluid replacement, which is similar to the lack of response commonly seen in cases of severe head injury that results in a central sympathectomy.

Cutaneous Signs and Symptoms

Skin symptoms may present as pruritus or formication only ("creeps"). It is important to keep in mind that some of these skin DCS manifestations may also be mediated by involvement of peripheral nervous system elements. The sensation generally passes within 20 to 30 minutes, and no treatment is necessary. A transient scarlatiniform skin rash may occur. Skin symptoms, however, may present with the appearance of mottled or marbled skin lesions; this condition is also referred to as *cutis marmorata*. This condition does not appear to carry excess risk for neurocirculatory compromise in hypobaric DCS (114)—in contrast to diving DCS, where it is a clear warning sign of more serious DCS—as was previously hypothesized (71). Therapy depends on the circumstances, in case of cutis marmorata in the setting of diving a full USN-Treatment Table 6 would be warranted, in the setting of hypobaric exposure an immediate USN-Treatment Table 5 may be appropriate depending on how rapidly the condition resolves following repressurization to ground level. Cutis marmorata associated with diving must alert the treating physician to the potential imminent development of more serious DCS manifestations and should be treated analogous to type II DCS (102).

Pitting edema, if seen alone, is considered a minor manifestation of DCS in that it will resolve spontaneously without sequelae. Pitting edema is thought to arise from lymphatic blockage by bubbles. It rarely results from altitude exposure. Localized pain in lymph nodes may occur as well and recompression typically provides prompt pain relief.

Constitutional Signs and Symptoms

Following decompressions to altitude, mild, transient fatigue is frequently encountered in the operational as well as research setting in subjects and chamber attendants. This symptom is usually ignored, although it may be accompanied by distinct malaise and lack of appetite. The significance and etiology of this fatigue has not been thoroughly investigated, but it may represent mild impairment of mental and nervous function. Severe exhaustion should alert the clinician; this may be an indicator of concomitant or impending more severe DCS and should prompt a detailed physical examination to avoid missing other subtle signs and symptoms (112).

Chronic Effects

Aseptic bone necrosis is a debilitating condition, common among divers and caisson workers. It has been described in merely one well-documented case following altitude exposure (115,116). The evidence to link aseptic bone necrosis with altitude DCS is anecdotal at best. From the diving literature we know that areas of bone infarction, if located in juxta-articular locations, rapidly lead to erosion of overlying cartilage and severe osteoarthritis. The shoulders, knees, and hips are the only joints affected. Early lesions are asymptomatic and are only found on radiographic surveys. The exact relationship between aseptic bone necrosis and episodes of DCS is unknown. The disease is seen when compressed air exposure occurs on a regular and frequent basis and is seldom seen in less than 1 year after beginning such exposures.

DIAGNOSIS AND MANAGEMENT OF DECOMPRESSION SICKNESS

DCS rarely occurs unless one of the following conditions exists:

1. Exposure to altitudes greater than 5,488 m (18,000 ft)
2. Exposure to altitude shortly following exposure to compressed gas breathing [e.g., self-contained underwater

breathing apparatus (scuba) diving or hyperbaric chamber exposure]. DCS has occurred while flying in pressurized aircraft at a cabin altitude as low as 1,372 m (4,500 ft) following scuba diving in the preceding 3 hours

The following procedures are highly recommended in all cases of DCS (including DCS pain only) persisting after a dive or after a flight:

1. Administer 100% O_2 using a well-fitted aviator's mask or anesthesia mask.
2. If a hyperbaric chamber is on-site, the patient should be immediately treated according to the proper Treatment Table.
3. If there is no on-site hyperbaric chamber, arrangements should be made to immediately transport the patient to the nearest hyperbaric facility capable of administering proper treatment. The patient should be kept on 100% O_2 by mask while awaiting and during transportation to the chamber. If the patient has DCS pain only, the symptoms of which clear completely without recurrence within 2 hours postexposure while awaiting transport, the transport to the hyperbaric chamber can be cancelled. If the symptoms occur outside of the 2-hour time window postexposure, then a hyperbaric therapy (Treatment Table 6) is advisable.
4. If DCS pain is relieved while awaiting transport but recurs, the patient should be transported to the hyperbaric chamber and treated even if symptoms are relieved again after recurrence.
5. Any patient with signs or symptoms of persisting neurologic DCS, chokes, or circulatory collapse should be immediately transported to the nearest hyperbaric chamber for treatment, regardless of whether the symptoms persist.
6. Transportation must be at or near the ground level P_B of the site at which the patient embarks. Aircraft used for the movement of these patients must possess this pressurization capability. In no case should the cabin PA be more than 305 m (1,000 ft) higher than the PA at the point of embarkation. If at all possible, it is best to avoid moving patients to a hyperbaric chamber located at a PA greater than 1,067 m (3,500 ft) higher than the point of embarkation.
7. Personnel tending to the patient during transport and during recompression therapy should be able to provide advanced cardiac life support (ACLS). It is crucial for the inside attendants to rigorously comply with recommended decompression stops and oxygen breathing at depth to avoid excess nitrogen onloading during hyperbaric therapy with the attendant risk of DCS upon decompression from the respective Treatment Table.
8. Return to flying no earlier than 72 hours after resolution of pain-only DCS or complete resolution of any neurologic signs/symptoms.

HYPERBARIC THERAPY FOR DECOMPRESSION SICKNESS

Physiologic Basis of Hyperbaric Therapy

Hyperbaric therapy is achieved by applying physical factors related to the pressure environment. The elevation of the partial pressure of inspired gases (O_2 with hyperbaric O_2 therapy) and the subsequent increase in the amount of the various gases that enter into physical solution in body fluids (washout dynamics) are of key importance. The use of hyperbaric O_2 therapy for treating DCS results hypothetically in some bubble size reduction, a positive nitrogen gradient to reduce the size of bubbles and resolve them, perfusion of ischemic tissues, and correction of local tissue hypoxia.

When an individual is exposed to a change in P_B, a bubble deep within the body tissues responds to the pressure change. During compression, the surrounding P_B is increased, producing a reduction in bubble volume in accordance with Boyle's law. Clinically, it is important to weigh the potential risk of use of high pressures (risk of oxygen toxicity and nitrogen onloading during air breaks) for a prolonged period of time versus the modest decrease in the physical size of any bubble (Figure 3-7). During compression, the bubble becomes smaller and the surface tension increases.

Applying hyperbaric pressure in treating DCS will, therefore, either eliminate the bubbles entirely or reduce their size to a significant extent. The amount of size reduction will depend on the absolute bubble size at the onset of therapy. Although some bubbles may not be eliminated completely by the initial application of pressure, their reduction in size aids in partially restoring circulation in the case of intravascular bubbles and reducing the mechanical effects of extravascular bubbles.

Bubbles that are too big to resolve upon the initial application of pressure will continue to decrease in size with the time spent at increased pressure while breathing 100% oxygen to continue denitrogenation. This gradual decrease in size is due to the diffusion of gases from the bubble to the surrounding tissues and fluids. Diffusion of gases from the bubble occurs because the partial pressure of gases within the bubble increases when the volume is reduced during compression. The elevated partial pressure of gases inside the bubble creates a gradient favorable for inert gas elimination from the bubble as tissue denitrogenation continues, as presented in Figure 3-8. This principle is the foundation of the efficacy of hyperbaric O_2 therapy. The oxygen window is equal to the partial pressure difference between the partial pressure of N_2 in the bubble and alveolar N_2 partial pressure. We can therefore understand that breathing high partial pressures of O_2 will increase the oxygen window by maximizing the above-mentioned partial pressure difference between the alveoli (zero nitrogen while breathing 100% oxygen) and the bubbles and body tissues. Figure 3-8 also shows that if the individual breathes air, the favorable gradient will lessen with time as the surrounding tissues and

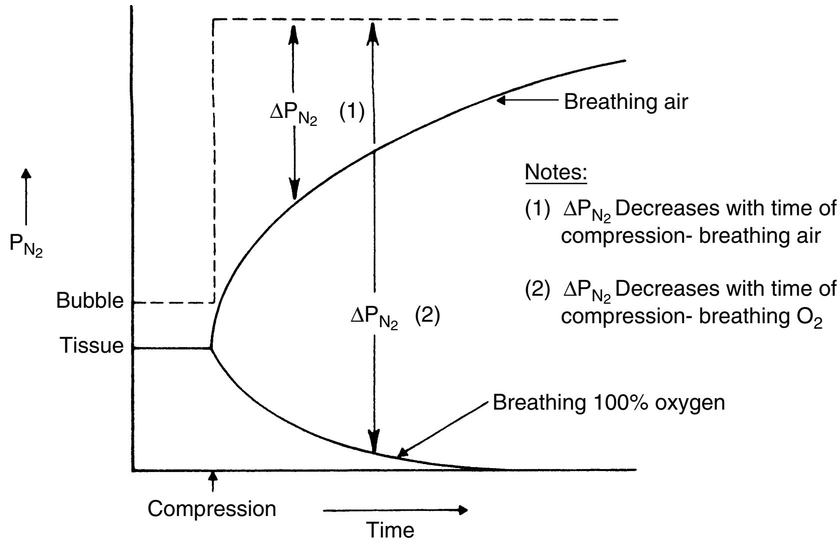


FIGURE 3-8 Bubble nitrogen gradients when breathing pure oxygen.

fluids approach equilibrium at the new N_2 partial pressure. Therefore, the bubble will be resolved more rapidly if the individual breathes 100% O_2 because a favorable gradient for nitrogen elimination from a bubble will improve with time, and the bubble will more rapidly diminish in size. During hyperbaric therapy, the patient intermittently breathes 100% O_2 at increased pressure. Breathing 100% O_2 provides an increased gradient for eliminating N_2 from evolved bubbles and aids in their resorption. The increased gradient also speeds the elimination of N_2 from supersaturated tissues, and thereby helps prevent further bubble formation. Therefore, if a sufficient time is spent at depth, all bubbles will resolve.

Hyperbaric oxygenation results in increased O_2 tension in the capillaries surrounding ischemic tissue. The increased O_2 tension extends the O_2 diffusion distance from functioning capillaries and corrects the local tissue hypoxia. Overcoming the tissue hypoxia tends to disrupt the vicious cycle of hypoxia-induced tissue damage that causes tissue edema and interferes with circulation and oxygenation.

Treatment of Altitude Decompression Sickness

Although the vast majority of DCS cases occurring at altitude will be completely relieved by descent to ground level, approximately 6.9% of cases may persist and require treatment (117). In addition, less than 1% of patients will experience the initial onset of symptoms of DCS after descent, so-called *delayed cases*. Deaths from altitude DCS are exceptionally rare in contrast to diving induced DCS.

Before 1959, more than 17,000 cases of altitude-induced DCS were documented. Of these cases, 743 were reported as serious, including 17 fatalities. Davis et al. (71), commenting on a review of these 17 fatalities, made the following observations. All died in irreversible shock that was unresponsive to fluid replacement and drug therapy. Almost all cases began as simple DCS pain, neurologic manifestations, or chokes, which only after several hours progressed to circulatory collapse and death. It should be noted that none of the 17 fatalities were treated by hyperbaric therapy. In their review of 145 cases of altitude DCS treated in hyperbaric chambers, these same authors emphasized that shock was the initial clinical picture in only one case, whereas seven other cases began with other manifestations and progressed to shock. In this series of patients, no fatalities occurred among those who were treated in hyperbaric chambers (71). In 1988, another fatality (68) occurred due to exposure to 8,537 m (28,000 ft) for more than 30 minutes secondary to a faulty canopy seal in a F-100 flight. The aviator had symptoms at altitude, delayed landing and complained of persistent dyspnea after landing, and finally reported to the emergency room with a 1-hour delay after landing; hyperbaric therapy was initiated 3 hours after presentation (transport to hyperbaric facility). The patient, who was overweight and 51 years, died 5.5 hours after presentation during hyperbaric therapy (USN Treatment Table 6A) with pulmonary symptoms (“chokes”) terminating in ventricular fibrillation.

As early as 1945, Behnke (40) advocated the use of compression therapy to treat cases of altitude DCS that did not resolve upon descent to ground level. It was not until 1959 that a USAF aviator was successfully treated by compression (106). In 1963, Downey et al. (118) using a human serum *in vitro* model, demonstrated the persistence, at ground level, of bubbles formed at altitude. Upon compression to pressures greater than sea level, the bubbles cleared. *In vivo* confirmation of Downey’s work was reported by Leverett et al. in 1963 (119).

Because many physicians have no training in recognition or treatment of altitude DCS, it is important for aircrew to be aware of the symptoms of DCS and the need to seek medical attention from informed personnel. Altitude DCS is typically resolved during descent to a lower altitude while breathing 100% oxygen in accordance with current USAF directives. Continued breathing of 100% oxygen on the ground for 2 hours is sometimes effective treatment for select mild cases of DCS that do not resolve completely during descent (120). The reason for resolution of symptoms with this procedure is twofold: (i) The gas emboli (bubbles) are subjected to increased pressure during descent which will reduce their size and effect (117); (ii) breathing 100% oxygen partially denitrogenates blood and tissues. This reduces the potential for bubble growth and results in shrinkage of existing bubbles in tissues adjacent to capillaries, where the diffusion gradient will favor nitrogen leaving the tissue and entering the denitrogenated blood.

DCS Treatment Synopsis

- 100% oxygen
- Descend as soon as practical
- Declare Inflight emergency
- Land at the nearest airfield with qualified medical assistance (military flight surgeon or civil aeromedical physician) available

HBO therapy is the standard of care, and it is successful in treating DCS symptoms which do not resolve before landing or which involve neurologic or pulmonary (respiratory) symptoms. The additional pressure of the hyperbaric treatment further reduces the size of existing bubbles. Breathing 100% oxygen during the HBO treatment ensures no further nitrogen is delivered to the tissues and helps to oxygenate tissues where bubbles may have blocked delivery of oxygenated blood. HBO treatment of DCS, whether from altitude or hyperbaric exposures, has been documented to be more successful if begun as soon as practical after symptoms appear. When symptoms are reported later, treatment is not as effective. The nature and severity of the symptoms dictate the specific hyperbaric profile for treatment and may require multiple treatments for complete resolution. The USAFSAM's Hyperbaric Medicine Division (FEH) serves as the primary source of information and consultation on treatment of DCS for the USAF.

Treatment of USAF altitude chamber reactors is guided by USAFSAM/FEH (Hyperbaric Medicine Division) directives based on time since treatment and the symptoms at time of treatment. Some treatment scenarios involve ground level oxygen and the rest utilize HBO therapy. HBO treatment scenarios include modified USN Treatment Table 5 and 6 profiles to 60 fsw (121) breathing 100% oxygen with air breaks to avoid oxygen toxicity. The profiles last from 135 to 285 minutes not including descent time. Treatment Table 6A to 165 fsw for 319 minutes is employed for treating air embolism and only rarely for DCS cases, which do not resolve with Treatment Tables 5 or 6. At 165 fsw, air or a nitrox mix is used to prevent oxygen toxicity. Owing to the renitrogenation that takes place at 165 fsw and the relatively small reduction in bubble size with the extra pressure (Figures 3-9A and 3-9B), Table 6A is generally not considered a good choice for treatment of DCS. The algorithm to assist in treatment shown in the subsequent text was developed at the USAFSAM Hyperbaric Medicine Division.

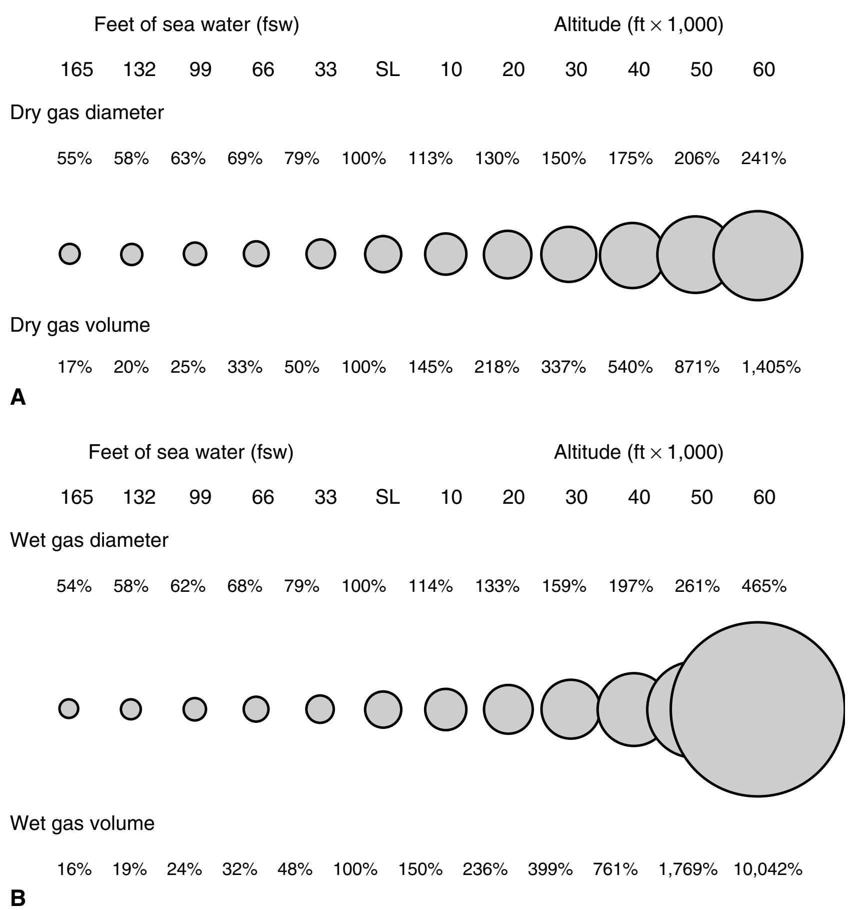


FIGURE 3-9 **A and B**: Bubble volume changes with altitude.

Of the approximately 1,000 cases of DCS observed in subjects during 20 years of altitude DCS research chamber activity at Brooks City Base, 89 subjects were treated with HBO by the Hyperbaric Medicine Division, all with complete resolution of symptoms. The remaining cases were successfully treated with 2 hours of ground level oxygen (GLO) (120) or with no treatment.

Treatment Procedures

If the aviator had only symptoms of joint pain that resolved upon recompression to one ATA from altitude, then the individual may be treated with 2 hours of 100% GLO, followed by 24 hours of observation. Should symptoms persist after recompression to ground level from altitude or recur, then transfer to a hyperbaric treatment facility should be arranged. The use of surface level 100% oxygen as a therapeutic modality applies only under select circumstances:

1. Altitude (NOT diving)-induced DCS only, bends pain only
2. Pain during the exposure or within 2 hours of exiting the altitude exposure
3. NOT for paresthesiae, neurologic symptoms or respiratory (chokes) symptoms
4. Successful therapy is disappearance of all symptoms after 2 hours of surface level 100% oxygen
5. Oxygen therapy should be continued for 1 hour after all symptoms have resolved
6. Minimum of 2 hours of oxygen is advisable even if symptoms resolve immediately
7. Maximum time on surface level 100% oxygen is 3 hours
8. If symptoms worsen or recur go to Treatment Table 5 or 6
9. If symptoms do not improve in 30 to 60 minutes go to Treatment Table 5 or 6
10. If symptoms do not resolve completely within 2 hours go to Treatment Table 5 or 6

The importance of a thorough but expeditious patient examination cannot be overemphasized; some patients may not report/be aware of subtle neurologic symptoms that actually might alter therapy. In case of a clear therapeutic emergency, that is, cardiovascular collapse, severe chokes, marked neurologic deficit, the neurologic examination is clearly not essential as a first priority. The patient presenting with stable symptoms, after a hyperbaric recompression, with a recurrence of symptoms or before initiating patient transport represents the situation where a thorough, repeat neurologic examination is most valuable. The examination may allow reclassification into a different treatment algorithm possibly modifying your choice of treatment tables as discussed in the subsequent text. The examination should allow a clearer definition of the anatomic area affected (supratentorial/infratentorial, spinal cord, peripheral nerves, muscle/musculoskeletal). Ideally, in the interest of reproducibility and consistency, such an examination should follow a standard protocol, possibly in the form of a DCS examination checklist (122).

Although a number of treatment tables are used successfully throughout the world, the USN Treatment Tables are considered authoritative for treating DCS in this country. Before 1964, air Treatment Tables were used in the therapy of DCS. The therapeutic success was not satisfactory and therefore Goodman and Workman (123) developed the oxygen Treatment Tables now labeled as Tables 5 and 6. The oxygen Treatment Tables were adopted by the USN in 1967 and have proved to be highly effective in treating DCS. Lack of response or worsening symptoms for pain-only DCS after ground level oxygen therapy warrants use of Treatment Table 5. If the symptoms do not disappear or worsen on a Treatment Table 5, then the patient is committed to Treatment Table 6.

Treatment Table 6 is reserved as a first step for cases involving the CNS or cardiopulmonary systems and for recurrences of previously treated DCS. The USN Treatment Table 7 is used only in life-threatening situations when other treatment tables have failed to resolve symptoms of serious type II DCS or cerebral gas embolism. Because patients treated on Table 7 will be in the hyperbaric chamber for at least 48 hours, this treatment should only be undertaken when all medical and nonmedical care of the patient can be provided in the chamber for this period of time. When long delays between onset and treatment occur, the manifestations of DCS become more serious. They seem to be aggravated by the development of secondary edema and vascular obstruction or impairment from thrombosis. Hyperbaric oxygenation in such circumstances probably provides more benefit than does the mechanical compression of bubbles.

Patients should stay in the vicinity of the treatment facility for at least 24 hours after hyperbaric therapy. Furthermore, exercise, alcohol, flying, diving, or altitude exposure should be avoided for 72 hours after the hyperbaric treatment. Patients should be told to stay well hydrated and expect some degree of fatigue after the hyperbaric chamber treatment. Delayed ear pain may occur, which may be prevented by performing a Toynbee or Valsalva maneuver before going to bed and again the next morning.

Adjuvants to Hyperbaric Therapy

Oxygen and hyperbaric therapy are the only definitive treatments for DCS. In serious cases of DCS, a marked loss of intravascular volume can occur by transudation of plasma across damaged capillary walls. Hemoconcentration producing hypoperfusion of tissue and sludging of red blood cells should be avoided or corrected by prompt and adequate administration of rehydration. Patients with CNS or respiratory DCS or arterial gas embolism should receive intravenous (IV) Ringer's lactate or normal saline solution (121). Solutions containing only Dextrose (e.g., D5W) should be avoided as they may contribute to edema as the dextrose is metabolized. Patients who are fully conscious may receive oral rehydration, typically 1 to 2 L of water, juice, or noncarbonated drinks are adequate. Frequent checks of urinary output are the best guide to the adequacy of the fluid therapy. Urinary output should be maintained at 1 to 2 mL/kg/hr.

Dexamethasone, 20 mg IV followed by 4 mg intramuscularly every 6 hours, may be useful in the prevention or treatment of CNS edema (124). IV methylprednisolone with an initial dose of 30 mg/kg followed by constant IV infusion at a rate of 5.4 mg/kg/hr may be used as well. Aside from the possible benefits in the treatment of cerebral edema, there is currently no conclusive evidence for a beneficial therapeutic impact of corticosteroid therapy on DCS outcome.

In cases of neurologic DCS affecting the spinal cord resulting in immobility, the prophylactic use of heparin, preferably low molecular weight heparin (LMWH), is recommended to prevent deep venous thrombosis (DVT) (125,126). Heparin *per se* does not appear to have a beneficial effect in the treatment of DCS aside from the prevention of DVT (127,128) and may hypothetically increase the risk of bleeding (spinal chord, brain, and inner ear may show evidence of hemorrhage in severe DCS). In spinal chord DCS, an indwelling urinary catheter should be placed because these patients commonly develop a neurogenic bladder.

The use of Lidocaine in antiarrhythmic doses (loading dose 1.5 mg/kg, followed by a maintenance drip rate of 1 mg/min) as a neuroprotective agent in DCS is currently under investigation; several studies have shown favorable results (129).

The use of IV perfluorocarbon emulsions combined with 100% O_2 in the prevention as well as therapy of DCS has shown promising results in animal studies and may become available for clinical use (130–133). Perfluorocarbon emulsions function as very efficient oxygen and nitrogen carriers, thereby improving tissue oxygenation and denitrogenation.

Cases of DCS following diving do not result in near drowning as frequently as do cases of cerebral air embolism; nevertheless, the possibility of near drowning must be considered and treatment begun when warranted. In such cases, intensive pulmonary care is mandatory. Endotracheal intubation, assisted ventilation with monitoring of end-tidal CO_2 (57), and appropriate correction of acidosis may be necessary.

None of the earlier procedures should delay movement of the patient to a hyperbaric chamber except when necessary as immediate life-sustaining measures. It is just as important, however, to institute or continue such procedures after hyperbaric therapy is begun as part of the overall intensive care management of serious cases.

Return to Flying Duty

Aeromedical disposition of aircrew who have DCS varies among the different branches of the US Department of Defense. The USAF has policies in place that allow return to flying duty 72 hours after a simple, fully resolved case of DCS not involving CNS symptoms. The aviator needs to be seen by his local flight surgeon who documents a normal neurologic examination before returning the aviator to flying status. DCS with neurologic involvement usually requires 72 hours of grounding. DCS with neurologic involvement that resolves without residual deficits requires a clearing evaluation by a neurologist, concurrence with the decision to return to flying status by the hyperbaric medicine physician at the Davis Hyperbaric Laboratory in San Antonio and the Major Command flight surgeon before return to flying status. Aviators with residual deficits after a DCS incident are disqualified from flying duties. The aviator may apply for a waiver and the decision will be made on a case-by-case basis after review and examination by the Aeromedical Consultation Service at Brooks City Base and their emanating recommendation will be the basis for the final waiver decision at Major Command level.

The USN follows the following policies: a simple, single episode of type I (pain only) DCS event results in grounding of the aviator for a period of 3 to 7 days. The aviator may return to flying duty thereafter, provided there are no residual deficits on physical examination. Type II DCS requires grounding for 14 to 30 days; return to flying status is possible provided there are no residual deficits on physical examination by the flight surgeon. Aviators with residual neurologic deficits may apply for a waiver and a review by the Hyperbaric Medicine Committee at the Naval Aerospace Medical Institute will consider each application on a case-by-case basis.

DIRECT EFFECTS OF PRESSURE CHANGES

Gas contained within body cavities is saturated with water vapor, the partial pressure of which is related to body temperature. Because body temperature is relatively constant (37°C), the partial pressure of the water vapor is also constant at 47 mm Hg. Therefore, the following relationship can be expressed as Boyle's law with reference to wet gas:

$$V_i\,(P_i - P_{H_2O}) = V_f\,(P_f - P_{H_2O}) \qquad [11]$$

where V_i is the initial volume of the gas; V_f is the final volume of the gas; P_i is the initial pressure of the gas in the cavity in mm Hg; P_f is the final pressure of the gas in the cavity in mm Hg; and P_{H_2O} is the partial pressure of water vapor (47 mm Hg at 37°C). Over a given pressure reduction, wet gas will expand to a greater degree than dry gas (Figures 3-9A and 3-9B). The relative gas expansion is a ratio of the final volume of the gas (V_f) to the initial volume (V_i) of the gas and is expressed in the following equation:

$$\text{Relative gas expansion} = \frac{V_f}{V_i} = \frac{P_i - P_{H_2O}}{P_f - P_{H_2O}} = \frac{(P_i - 47)}{(P_f - 47)} \qquad [12]$$

Figure 3-10 illustrates the increased volume of wet gases at a given pressure over that of a dry gas.

When one experiences a change in ambient pressure, a pressure differential is established between gas-containing body cavities and the external environment. To the extent that gas can move between body cavities and the external environment, this pressure differential will be relieved. It can also be relieved by a change in the volume of the body cavity

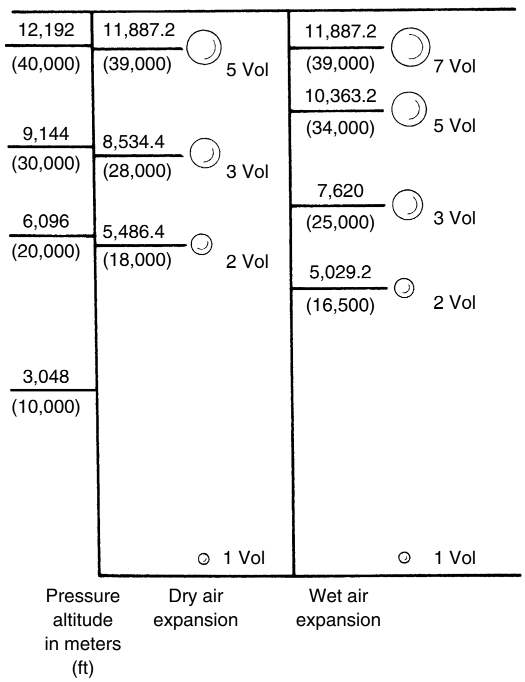


FIGURE 3-10 Volumes of wet and dry gases.

(compliance). When the pressure differential is not relieved, pathologic effects on involved tissues are likely to occur. The magnitude of the pathologic effects is related to the ratio of the pressure of the gas within the affected body cavity to the ambient pressure and not to the absolute value of the pressure differential. This is predictable from examining the pressure–volume relationships of Boyle's law. Therefore, divers, for example, experience more difficulties with the mechanical effects of pressure change when descending from sea level to 33 fsw [10 meter seawater (msw)] (Equations 13 and 14), than they do when descending from 99 to 132 fsw (30 to 40 msw) (Equations 15 and 16). Note that the pressure differential is identical for both circumstances, but the pressure ratio is considerably different.

Pressure differential:

$$P_f - P_i = 1520 \text{ mm Hg} - 760 \text{ mm Hg} = 760 \text{ mm Hg} \quad [13]$$

Pressure ratio,

$$\frac{P_f}{P_i} = \frac{1520 \text{ mm Hg}}{760 \text{ mm Hg}} = 2 \quad [14]$$

Pressure differential:

$$P_f - P_i = 3800 \text{ mm Hg} - 3040 \text{ mm Hg} = 760 \text{ mm Hg} \quad [15]$$

Pressure ratio,

$$\frac{P_f}{P_i} = \frac{3800 \text{ mm Hg}}{3040 \text{ mm Hg}} = 1.25 \quad [16]$$

Medically significant pressure changes occur in both flying and diving. There is a marked difference, however, between these two operations with respect to the magnitude and rate of the pressure changes. An aviator descending to sea level from 7,620 m at 1,520 m/min (25,000 ft at 5,000 ft/min) will experience a total pressure change of 478 mm Hg at a rate of 2.3 mm Hg/s. A diver descending from sea level to 165 fsw (50 msw) at a rate of 60 ft/min (18 m/min) will experience a total pressure change of 3,800 mm Hg at a rate of 23 mm Hg/s.

In general, it is possible to successfully cope with the changes in P_B that occur within the flying or diving envelopes. As long as the pressure in the various body cavities can equalize with the ambient pressure, large pressure changes can be tolerated. For example, meaningful work has been performed by aviators at pressures equivalent to 0.1 (ATA) atm abs (17,982 m or 59,000 ft) and by divers at pressures equivalent to 69 atm abs (686 m or 2,250 ft).

If equalization of pressure is not attained, difficulties ranging from mild discomfort to severe pain, tissue damage, and complete incapacitation will be experienced. The areas of primary concern are the lungs, middle and inner ear, paranasal sinuses, teeth, and the gastrointestinal tract.

The Lungs: Pulmonary Barotrauma and Arterial Gas Embolization

Unless air is continually exchanged between the lungs and the outside environment during changes in ambient pressure, severe pathologic disorders can result from the effects of Boyle's law. Airflow during pressure change will not occur with voluntary breathholding or the apneic phase of tonoclonic seizure.

Consider the potential problem of a breathholding descent during diving. The average total lung capacity is 5,800 cm^3. The residual volume (i.e., the volume to which the lungs can be reduced with forceful expiration) is 1,200 cm^3. If the air volume within the lungs is reduced below 1,200 cm^3, the actual lung volume will decrease no further due to the elastic and fibrous skeletal structure of the lung tissue. The volume deficit is made up by the leakage of plasma and whole blood into the lungs. This is the classic description of the pathologic condition called *lung squeeze* and is more common in breathholding diving than in descent from altitude. To achieve lung squeeze, the air volume within the lungs must be reduced to approximately 20% of the original volume. To achieve this on descent from altitude, an aviator would have to make a breathholding descent from 11,890 m (39,000 ft) to sea level. A breathholding dive to 132 fsw (40 msw), however, will result in such a fivefold decrease in the original lung volume. Such a dive is well within the capabilities of many expert divers.

In compressed gas diving, respirable gas is supplied to the diver from the surface, from a diving bell or hyperbaric chamber, or from a scuba. The gas may be supplied through regulators designed to match intrapulmonary gas pressure to the surrounding ambient pressure. The compressed gas–supplied diver avoids lung squeeze on descent but runs an added risk on ascent. During ascent to the surface, the diver must continually equilibrate the intrapulmonary pressure to the surrounding pressure. This equilibration is usually accomplished by releasing gas from the lungs by normal breathing or, in the event of the loss of gas supply at depth, by slow continual exhalation on ascent. Failure to do so results in intrapulmonary gas expansion according to Boyle's law and, after the elastic limit of the thorax is reached, a relative rise of intra-alveolar pressure. A rise in intra-alveolar pressure of 50 to 100 mm Hg above ambient pressure is sufficient to force gas into extra-alveolar compartments, resulting in one or more of the clinical conditions grouped under the term *pulmonary overpressure accidents/pulmonary barotrauma*.

Pressure differentials sufficient to cause a pulmonary overpressure accident in the compressed gas–supplied diver can occur on ascents as shallow as from 2 m (6.6 ft) to the surface. In the aviator, concern regarding pulmonary barotraumas is justified as well. Sufficient pressure differentials can be attained due to rapid decompression at high altitude, possibly coupled with exacerbating factors such as concomitant performance of an anti-G straining maneuver against a closed glottis and concomitant positive pressure breathing.

Autopsies of fatalities following pulmonary overpressure accidents have demonstrated extra-alveolar gas in essentially every tissue examined. Following such an accident, however, the clinical picture seen will be that of arterial gas embolism, mediastinal and subcutaneous emphysema, and/or pneumothorax. The latter two manifestations are recognized by physical and radiographic examination and are managed by conventional measures. The manifestations of arterial gas embolism have an immediate onset following the rapid pressure reduction and may include loss of consciousness, local or generalized seizures, visual field loss or blindness, weakness, paralysis, hypoesthesia, or confusion. A patient presenting with any of these signs or symptoms within 15 minutes of exposure to a rapid pressure reduction must be assumed to have suffered an arterial gas embolism and be treated emergently for such.

Predisposing Factors

In addition to breathholding during ascent, pulmonary overpressure accidents can also occur as a consequence of preexisting disease that limits the egress of gas from the lungs. Therefore, the risk is increased by asthma, chronic bronchitis, air-containing pulmonary cysts, and other obstructive airway disease. Some pulmonary overpressure accidents have occurred without demonstrable cause in patients who exhaled during ascent and had no subsequent lung disorders. In these cases, local pulmonary air trapping is thought to have occurred by redundant tissue, mucous plugs, or similar mechanisms establishing a one-way valve in a small air passage, which allowed gas to pass during compression but not during decompression.

In the context of aeromedical evacuations of casualties, it is important to remember that an increasing number of cases of gas embolism are caused by the introduction of air or other gas into the arterial or venous system during surgical procedures or following the establishment of indwelling arterial catheters. With the increasing use of indwelling catheters and surgical procedures involving invasive instrumentation of the cardiovascular system, the number of gas embolism cases has also increased. Stoney et al. (134) have estimated that the accidental introduction of air through arterial lines occurs in more than 1 in 1,000 cases.

Diagnosis

The most difficult differential diagnosis is between gas embolism and neurologic DCS when decompression is involved. This diagnosis is important because of the need to select a proper Treatment Table. The key factor in reaching a proper diagnosis is the time before the onset of symptoms and history. The onset is immediate with gas embolism, with symptoms usually occurring swiftly after rapid pressure reduction.

The diagnosis of a surgical gas embolism should be considered in any patient with indwelling arterial or venous lines (particularly a central line). The sudden onset of seizure or coma is frequently the presenting sign. Venous gas embolism is more common and much less of a problem due to the microfiltration capability of the lungs. Nonetheless, it may present as a systemic embolism in the presence of a PFO with right to left shunting, ASD/PFO, pulmonary microcirculation, or through arteriovenous (AV) shunts (42).

In surgical cases, general anesthesia may mask the unusual symptoms; however, failure of the patient to awaken normally or the presentation of an unexplained neurologic deficit should alert one to the diagnosis of possible intraoperative gas embolism. A neurologic examination may reveal a myriad of CNS findings depending on the location of the gas. Funduscopic examination may reveal arteriolar bubbles in some instances. Computed tomographic (CT) scanning or MRI of the head may be used diagnostically when it is immediately available, but therapy should not be delayed while waiting for an imaging procedure.

In the diagnosis and treatment of gas embolism, time and appropriate life support measures (ACLS) are of the essence. Although some patients survive a delay of up to 24 hours, the experience of treatment facilities, with a mortality range of 20% to 25%, indicates that time from embolization to treatment is a most important factor.

Treatment

To provide effective therapy for gas embolism, it is important to remember the basic difference between DCS (air or gas bubbles evolving from solution) and gas embolism (gas bubbles that enter the arterial or venous circulation directly). Although the manifestations of DCS are diverse, they are rarely fatal when treated by proper hyperbaric therapy within hours to days of occurrence. Conversely, the onset of gas embolism is a sudden, dramatic, and immediately life-threatening event. Bubbles obstruct the systemic or pulmonary arterial circulation. As decompression continues, they expand to produce local endothelial cell damage and herniation into the vessel walls. In addition, plasma proteins react to the invading bubbles by denaturization and attachment to the bubble wall. Activation and agglutination of platelets to the bubbles occur (61), with release of very potent vasoactive amines and prostaglandins, which produce immediate hypoxia symptoms that may appear as neurologic deficits.

The rationale for hyperbaric therapy for DCS also applies to the management of gas embolism: mechanical compression of bubbles and hyperbaric oxygenation of tissues. Because of the massive amounts of air that are often introduced into the cerebral circulation of gas embolism victims, it is usually necessary to mechanically compress the entrapped air maximally.

The Trendelenburg (30° head-low) position has been considered the ideal position to further decrease the likelihood of further introducing air volume into the CNS. This position increases cerebral hydrostatic pressure and, in some cases, forces small bubbles from the arterial circulation across the cerebral capillary bed into the venous circulation, where they produce less potential harm to the victim. At the same time, this position may enhance cerebral edema formation. It is currently not a routine recommendation, unless the patient benefits from the augmented cardiac output. Supine positioning of the patient is preferred. It must be emphasized that 100% O_2 breathing cannot be administered at 6 ATA abs (Treatment Table 6A) due to the extremely short time to CNS O_2 toxicity. Convulsive seizures would occur in less than 5 minutes. Elevated oxygen percentages, however, can be administered in the form of 50/50 Nitrox (a mixture of 50% O_2 and 50% N_2). This mixture will assist in correcting tissue hypoxia and ischemia because of the improved oxygen diffusion distance.

When it has been determined that maximum benefit has been attained from the mechanical compression of the entrapped air, the patient must be brought to shallower depths so that 100% O_2 can be administered. Because of the advantages of treating with 100% O_2, the USN Diving Manual suggests initial compression to 2.8 atm abs (18 msw or 60 fsw) for one 20-minute oxygen breathing period before making the decision on whether to pressurize to 6 ATA (50 msw or 165 fsw) (102).

Hyperbaric therapy is the only definitive treatment for AGE. All other methods are adjunctive in nature. As soon as the diagnosis is made, the patient should be placed in the chamber and rapidly compressed with air to 60 fsw (18 msw, 2.8 ATA). The patient is placed on 100% O_2 for a 20-minute breathing period. If symptoms improve, treatment continues on Table 6. If symptoms do not change or worsen, the patient is compressed to 6 ATA (165 fsw, 50 msw) and treatment continues on Table 6A.

Variation from the standard Table 6A is potentially harmful to both the patient and inside observers and should not be done without prior consultation with experts in diving medicine.

Adjunctive measures that should be used in the treatment of AGE are IV fluids and possibly steroids in pharmacologic doses (see also discussion "adjunctive measures to hyperbaric therapy" in the preceding text). Hemoconcentration is frequently seen in AGE and may be related to tissue hypoxia and edema. Divers are also commonly dehydrated secondary to pressure diuresis and lack of normal oral fluid intake. Vigorous hydration is important to minimize sludging and obstruction of microvascular blood flow caused by the elevated hematocrit, while avoiding fluid overload. Balanced saline solution (Ringer's lactate) or isotonic saline without dextrose should be administered intravenously at the rate of 1 L/hr until the patient voids or is catheterized for at least 500 mL. Sugar (glucose) is specifically not given to prevent further dehydration secondary to glycosuria and a resultant osmotic diuresis as well as the potential for edema formation. Once adequate hydration is achieved, the rate is slowed to 150 to 200 mL/hr for the remainder of the treatment.

Dexamethasone may be administered intravenously in a dose of 20 mg followed by 4 mg intramuscularly every 6 hours for 24 to 48 hours (124); this may prove to be beneficial in cases with evidence of cerebral edema. Till now, there is no conclusive evidence showing a clear therapeutic benefit of corticosteroids in this context; therefore, the question of their use remains open in this setting. There is furthermore no supportive evidence for the idea that steroids may increase an individual's susceptibility to oxygen toxicity. Anticoagulant or antiplatelet medications are not recommended as routine therapy of AGE, unless neurologic symptoms cause an inability to walk, in that case adjunctive DVT prophylaxis with LMWH should be initiated (125–128).

Transport of Patients

One-hundred percent O_2 should be started as soon as possible, using a tightly fitted aviator's or anesthesia-type mask. The patient should be placed in a recumbent position while awaiting and during transport to the hyperbaric chamber. If transport is required, it is of utmost importance to maintain near sea-level pressure. The use of "low-flying" helicopters is contraindicated if ground transportation is available. Even slight decreases in pressure cause bubble enlargement and may significantly alter the clinical course of the patient.

During transport, IV fluids should be administered using balanced saline solutions or normal saline. Patients having CNS or respiratory DCS or AGE should be accompanied during transport by personnel capable of providing intensive respiratory and ACLS care.

Immediate hyperbaric therapy is essential. Good response, however, has been seen in some cases after long delays before reaching the chamber. This makes it mandatory to give the patient the benefit of a trial of compression and hyperbaric O_2 even in the late case. Of course, every minute that elapses before the start of compression makes the prognosis more guarded.

Return to Flying Duties after Arterial Gas Embolization

A decision as to when and if to return a person to flying duties following AGE is complex. Consideration must be given to the circumstances under which the gas embolism occurred and the presence or absence of underlying pulmonary pathology (as predictors of recurrence) as well as evidence for residual neurologic pathology. A rational approach is to consider a cerebral gas embolism ahead injury. The patient evaluation strategies following head injuries used by the appropriate regulating agencies (Federal Aviation Administration or military authorities) provide a basis for decisions on return to flying duties. In no case, however, should a patient return to such duties earlier than 3 weeks following such an incident to assure complete pulmonary healing has occurred.

Other Gas-Containing Cavities

Direct effects of pressure change on the ear, paranasal sinuses, and teeth are described in Chapter 15 and Chapter 20. This section addresses effects on the body and the important distinction between wet and dry gas and the implications of pressure changes on medical equipment.

Water Vapor and Gas Expansion

The mechanical effects of expansion and contraction of a trapped physiologic gas follow Boyle's law closely due to the relatively constant temperature of human tissue where gases are located. During decompression (ascent), trapped gases would expand because a differential pressure develops as the external pressure decreases. Many trapped gases remain essentially constant in volume due to their structure, for example, sinuses and the middle ear. Instead of responding by increasing volume, these trapped gases exert a differential pressure on surrounding tissues, which can cause severe, potentially disabling pain and potential physical damage to tissues.

The constant pressure (47 mm Hg) of water vapor at body temperature plays an increasing role in gas expansion during ascent as the partial pressures of the other expanded gases decrease. For example, water vapor makes up only 1% of the volume of a trapped gas bubble at 6 atmospheres (165 fsw) and 6% at sea level, but 33% of a trapped gas bubble at 40,000 ft. Due, in part, to the water vapor occupying more of the available pressure in alveoli, P_{AO_2} becomes extremely low above 45,000 ft. Even with 30 mm Hg of additional pressure applied to the lungs through pressure breathing for altitude (PBA) at 50,000 ft and 60 mm Hg of PBA at 60,000 ft, the P_{AO_2} is the same as breathing air above 18,000 ft.

At this writing, no pulse oximetry results have been obtained from humans using current oxygen equipment during exposure to 60,000 ft in an altitude chamber while breathing 100% oxygen with 70 mm Hg of PBA.

Above 63,000 ft, Armstrong's line, an unprotected human would experience vaporization of tissue water because the ambient pressure is 47 mm Hg, the same as the partial pressure of water at body temperature. The vaporization of body water above Armstrong's line is referred to as *ebullism*. Ebullism is different from embolism, which results from respiratory air being forced into the circulation by an overpressure in the lungs. The altitude or pressure at which ebullism occurs varies with the temperature and pressure in specific tissues. As an example, peripheral tissues are at a lower temperature than internal tissues and could ebullize at a lower pressure (higher altitude). Similarly, blood pressure in the arterial system would result in ebullism at lower pressure, higher altitude, than 63,000 ft. Any artificial increase in pressure around the body would also lower the potential for ebullism. One mechanism is a pressure suit and another is pressure PBA, which keeps the lung at a higher pressure. Although not protecting the rest of the body, PBA can at least provide a temporary increase in oxygen available to the tissues. Current equipment is inadequate to provide sufficient partial pressure of oxygen to tissues above 60,000 ft, even with assisted pressure breathing for altitude (APBA). This involves the use of a counterpressure jerkin worn to allow 60 mm Hg of pressure to be tolerated for more than a couple minutes.

Effects of Trapped Gases during Pressure Change

Because the volume of a sphere is a function of the cube of its radius and the diameter only twice the radius, a large volume change represents a relatively small change in diameter. However, it is the pressure differential, not volume change, which results in most of the effects listed in the subsequent text.

- Expansion of trapped gastrointestinal gas.
- Barotitis media (ear block) may be defined as an acute or chronic traumatic inflammation of the middle ear produced by a pressure differential (either positive or negative) between the air in the tympanic cavity and contiguous air spaces and that of the surrounding atmosphere. To alleviate the pressure differential, several maneuvers can be performed (Toynbee, Valsalve, Frenzel, etc.). The Toynbee maneuver entails pinching your nose, closing your mouth, and swallowing, thereby resulting in decreasing nasopharyngeal pressure against middle ear and Eustachian tube pressure. The Valsalva maneuver involves increasing the nasopharyngeal pressure against a closed Eustachian orifice; pinching your nose and blowing while your mouth is also closed. The Frenzel maneuver may also be performed by thrusting the jaw forward to open the Eustachian tube, thereby providing a path for equalization of pressure.
- Barosinusitis (sinus block) is an acute or chronic inflammation of one or more of the nasal accessory sinuses produced by a pressure difference (usually negative) between the air in the sinus cavity and the surrounding atmosphere. The condition is characterized by pain in the affected region typically during descent; this pain can develop suddenly and be so severe that the individual will be severely distracted and incapacitated.
- Barodontalgia (tooth pain) is also a case of a trapped gas exerting positive or negative pressure on surrounding tissue as a result of the difference between the pressure inside the tooth or the apical root of the tooth in the maxillary sinus and the pressure outside the tooth.
- Lung overinflation due to breath-hold or inadequate equalization of pressure during decompression can result in serious problems.
  - Pulmonary overexpansion
    - Pulmonary embolism (air in arterial circulation)

- Pneumothorax (air in lung pleural cavity)
- Pneumomediastinum (air in the mediastinum)

The Gastrointestinal Tract

Gas is normally contained in the stomach and the large bowel. As previously discussed, wet gases expand to a greater extent than do dry gases. Expansion within the closed confines of the gastrointestinal tract during ascent can cause stretching of the enclosing organ and produce abdominal pain. In addition to pain, respiration can also be compromised by gas expansion, forcing the diaphragm upward. If pain is allowed to proceed and relief is not obtained by belching or the passing of flatus, flight operations will be jeopardized. Severe pain may cause a vasovagal reaction with hypotension, tachycardia, and fainting. The best treatment of gastrointestinal tract discomfort due to gas expansion is the avoidance of gas-producing foods. Chewing gum may promote air swallowing and should be avoided at least during ascent. The crewmember should be instructed to pass gas when discomfort occurs. Abdominal massage and physical activity may promote the passage of gas. If this is unsuccessful, a descent should be initiated to an altitude at which comfort is achieved.

Other Gas-Containing Cavities

Direct effects of pressure change on the ear, paranasal sinuses, and teeth are described in Chapter 18. This section addresses these effects on the gastrointestinal system and on medical equipment.

Effects of Pressure Change on Medical Equipment

Varying volumes of gas may be trapped in medical equipment being used in the aerospace or hyperbaric environment. Examples of such equipment include drip chambers for IV fluids, endotracheal cuffs, water traps used with chest tubes, and sphygmomanometer cuffs.

During ascent, an unvented sphygmomanometer cuff will inflate and tighten around a patient's arm. If air is used to inflate an endotracheal cuff, significant ambient pressure reductions, particularly as seen with ascents from hyperbaric environments, can cause tracheal mucosal sloughing if allowed to persist. A wise precaution is to inflate endotracheal cuffs with normal saline rather than air in such environments. Water levels in water traps should be checked often or opened to ambient pressure when significant changes in pressure occur. The air space in IV line drip chambers will decrease in volume with increased pressure in hyperbaric chambers. Additional air will have to be added to the drip chamber to monitor the drip rate. On ascent, the volume of air will increase, and if added air is not replaced with fluid, IV air will inadvertently be administered.

The possible effects of changes in pressure on all medical equipment should be considered before such equipment is used either in a hyperbaric chamber or in flight. When possible, the equipment should be functionally tested in the pressure environment in which it is to be used before it is used with patients.

Ebullism

With the planned expansion of the operational ceiling for new, modern fighter aircraft (e.g., F-22 Raptor, Eurofighter 2000) to 18,287 m (60,000 ft), we are approaching the atmospheric zone which may result in human exposures to ambient pressures below 47 mm Hg. This is the equivalent of the saturated water vapor pressure at body temperature (37°C). Upon exposure to such an environmental pressure, spontaneous boiling and degassing of body tissues and fluids will occur. This process is referred to as *ebullism* and the pressure-equivalent altitude at which it is expected to occur is referred to as the *Armstrong line* [19,201 m (63,000 ft)]. Owing to variations in pressure and temperature in the body, ebullism may occur in exposed human tissues as low as 16,763 m (55,000 ft), or higher in the case of tissue below body temperature and partly pressurized by an anti-G suit or a counterpressure jerkin. Therefore, referring to the "Armstrong line" as "Armstrong zone" would probably be more appropriate. The data that are available on the physiological changes occurring in this extreme pressure environment are derived from animal studies and a few accidental human exposures (135).

Animal studies (unprotected exposures) have shown rapid loss of consciousness (within 9–12 seconds), immediate tissue hypoxia, rapid increase in venous pressures, circulatory arrest (in seconds), apnea, and spastic rigidity within 30 seconds followed by flaccid paralysis. Provided that the structural integrity of lungs, heart, and cerebrum is maintained, recovery after exposures to 90 to 210 seconds of a hard vacuum is possible.

In one case of accidental exposure to 36,574 m (120,000 ft) during a test of a space suit, pressurization of the suit was lost and the subject remembered the sensation of his saliva boiling on his tongue. Rapid recompression resulted in regaining of consciousness at 4,267 m (14,000 ft) and the subject was not hospitalized after the incident and did not have any apparent complications. In a second incident, an individual was exposed to 22,554 m (74,000 ft) for 3 to 5 minutes in an industrial setting without any protective equipment. The individual was comatose with decerebrate posturing and had frank pulmonary hemorrhage after the exposure. Aggressive HBO and intensive care therapy resulted in full recovery without any evidence of neurologic deficits after the incident (1 year after the exposure neurologic testing was above baseline) (134).

There are currently no medical treatment protocols available for ebullism, as it was thought that such an exposure would likely not be survivable. The cases given in the preceding text illustrate the need for aggressive therapy aimed at reestablishing pulmonary gas exchange and support circulation. Hyperbaric O_2 therapy or at least 100% ground level O_2 needs to be considered together with aggressive intensive care therapy.

The quest to fly higher and dive deeper has expanded man's pressure environmental envelope well beyond that to which he is physiologically adapted. Pathologic changes resulting from exposure to these environments have defined new sets of clinical syndromes specifically related to pressure changes. Studies of the pathophysiology underlying these syndromes have unmasked two separate categories of disorders: indirect effects of pressure change resulting from the evolution of gas from solution and direct effects of pressure change on gas-containing body cavities. In addition, it is now recognized that the pressure environment represents a physiologic continuum from the increased pressures encountered by divers to the decreased pressures encountered by aviators and astronauts. This continuum is dramatically exemplified by the diver who surfaces safely only to experience DCS a few hours later while flying at low altitude.

As we have learned more about the physiologic changes that occur with changes in pressure, we have been able to develop rational treatment methods to cope with the medical disorders they bring about. Therefore, hyperbaric therapy, with specific treatment profiles for mild and severe DCS and for gas embolism, has lessened mortality and the incidence of permanent residual deficits. Adjuvants to hyperbaric therapy are increasing our ability to deal with these disorders.

CONCLUDING REMARKS

Advances in technology have allowed the development of systems capable of transporting air and space crewmembers into increasingly more severe pressure environments. The increased altitudes in the operational ceilings of the next generation fighter aircraft as well as the extensive EVA necessary to construct the ISS have drawn renewed attention to the disease processes associated with the changes in ambient pressure in the operational aerospace environment. Technologic advances have made possible the development of the life-support equipment necessary to prevent the pathophysiologic consequences of exposure to these environments. Unfortunately, the development of practical, effective life-support systems tends to lag behind the development of transport systems. Historically, this lag resulted from a lack of knowledge about the physiologic consequences of exposure to hostile environments. The effective and safe use of advanced flying and diving systems depends on our ability to educate the operators about the risk and symptomatology of DCS, efficient reporting mechanisms of DCS incidents, continuous reassessment of our clinical classification, documentation and evaluation of DCS, and the creation of effective risk-mitigation, risk-quantification, and risk-prediction strategies for the environment the operators face.

ACKNOWLEDGMENTS

Segments from the third edition's chapter, Decompression Sickness, authored by Jan Stepanek are included. We are grateful for the patient, critical review of the manuscript and comments by the editorial team. I appreciate the expertise, perspective, and contribution of my coauthor James Webb. I thank Dr. Hursh from the Brooks City Base Davis Hyperbaric Facility for his review of the aspects of manifestations of DCS and therapy of DCS and AGE.

REFERENCES

1. Muhm JM, Rock PB, McMullin DL, et al. Effect of aircraft-cabin altitude on passenger discomfort. *N Engl J Med* 2007;357(1):18–27.
2. Wu T. A Tibetan with chronic mountain sickness followed by high altitude pulmonary edema on reentry. *High Alt Med Biol* 2004;5(2):190–194.
3. Messner R. *Everest, expedition to the ultimate*. Seattle: The Mountaineers, 1999:275.
4. West JB. Climbing Mt. Everest without oxygen: an analysis of maximal exercise during extreme hypoxia. *Respir Physiol* 1983;52(3): 265–279.
5. West JB, Hackett PH, Maret KH, et al. Pulmonary gas exchange on the summit of Mt. Everest. *J Appl Physiol* 1983;55(3):678–687.
6. Hackett PH, Roach RC. High-altitude illness. *N Engl J Med* 2001; 345(2):107–114.
7. Klocke DL, Decker WW, Stepanek J. Altitude-related illnesses. *Mayo Clin Proc* 1998;73(10):988–992; quiz 992–3.
8. Honigman B, et al. Acute mountain sickness in a general tourist population at moderate altitudes. *Ann Intern Med* 1993;118(8): 587–592.
9. Hackett PH, Roach RC. High-altitude medicine. In: Auerbach P, ed. *Wilderness medicine*. Philadelphia: Mosby, 2001.
10. Sampson JB, Cymerman A, Burse RL, et al. Procedures for the measurement of acute mountain sickness. *Aviat Space Environ Med* 1983;54(12 Pt 1):1063–1073.
11. Markovic D, Kovacevic H. Recompression therapy of mountain sickness. *Arh Hig Rada Toksikol* 2002;53(1):3–6.
12. Roach R, Stepanek J, Hackett PH. In: Pandolf BR, ed. *Medical aspects of harsh environments*. Washington, DC: Office of the Surgeon General of the United States Army, Borden Institute, Walter Reed Army Medical Center, 2002:765 ff.
13. Hackett PH, Rennie D, Levine HD. The incidence, importance, and prophylaxis of acute mountain sickness. *Lancet* 1976;2(7996): 1149–1155.
14. Menon ND. High-altitude pulmonary edema: a clinical study. *N Engl J Med* 1965;273:66–73.
15. Sime F, Monge C, Whittembury J. Age as a cause of chronic mountain sickness (Monge's disease). *Int J Biometeorol* 1975;19(2): 93–98.
16. Ward MP, West JB. *High altitude medicine and physiology*, 3rd ed. New York: Oxford University Press, 2000:433.
17. Wiedman M, Tabin G. High-altitude retinal hemorrhage as a prognostic indicator in altitude illness. *Int Ophthalmol Clin* 1986; 26(2):175–186.
18. Wiedman M. High altitude retinal hemorrhage. *Arch Ophthalmol* 1975;93(6):401–403.
19. Nicogossian A, Huntoon CL, Pool SL, et al. eds. *Space physiology and medicine*. Philadelphia: Lea & Febiger, 1998:300.
20. Asker JR. US, Russian suits serve diverse EVA goals. *Aviat Week Space Technol* 1995;143(3):40–43.
21. West JB. Improving oxygenation at high altitude: acclimatization and O2 enrichment. *High Alt Med Biol* 2003;4(3):389–398.
22. Denison DM, Ledwith F, Poulton EC. Complex reaction times at simulated cabin altitudes of 5,000 feet and 8,000 feet. *Aerospace Med* 1996;10:1010–1013.
23. Ernsting J. Prevention of hypoxia-Acceptable compromises. *Aviat Space Environ Med* 1978;49:495–502.
24. West JB. Acclimatization to high altitude: truths and misconceptions. *High Alt Med Biol* 2003;4(4):401–402.

25. Balldin UT, Dart TS, Whimore J, et al. *The effects of 12 hours of low grade hypoxia at 10,000 ft at night in special operations forces aircraft operations on cognition, night vision goggle vision and subjective symptoms*. USAF, Air Force Research Laboratory, 2007:40; www.dtic.mil.
26. Lenfant C, Sullivan K. Adaptation to high altitude. *N Engl J Med* 1971;284(23):1298–1309.
27. Kindwall E. A short history of diving and diving medicine. In: Bove AA, ed. *Diving medicine*. Philadelphia: WBSaunders, 1997.
28. Bert P. *La pression barométrique*. Columbus: College Book Company, 1943. ed. 1878, Paris, France.: Masson.
29. Von Schrötter H. *Der Sauerstoff in der Prophylaxe und Therapie der Luftdruckerkrankungen*. Berlin:1906.
30. Boycott A, Damant GCC, Haldane JS. The prevention of compressed-air illness. *J Hyg Camb* 1908;8:342–443.
31. Henderson Y. Effects of altitude on aviators. *Aviation* 1917;2: 145–147.
32. Jongbloed J, *Bijdrage tot de Physiologie der Vliegers op groote Hoogten*, in *Habilitation Thesis*. University of Utrecht, 1929.
33. Jongbloed J, The composition of alveolar air in man at altitudes up to 14'000meters; partly without oxygen supply: the mechanical effect of very low atmospheric pressure, in: *Intenational. Air Congress. Vth Congress*, The Hague, 1930:1418.
34. Barcroft J, Margaria R, Douglas. Muscular exercise at low barometric pressures. *Arch Sci Biol* 1931;16:609–615.
35. Engle E, Lott A, Man in flight: biomedical achievements in aerospace, in *Doctors in the sky.*. Annapolis: Leeward Publications, Inc.; 1979:62.
36. Boothby W, Lovelace WR. Oxygen in aviation. *J Aviat Med* 1938; 9:172–198.
37. Spencer MP. Decompression limits for compressed air determined by ultrasonically detected blood bubbles. *J Appl Physiol* 1976;40(2):229–235.
38. Bayne CG, Hunt WS, Johanson DC, et al. Doppler bubble detection and decompression sickness: a prospective clinical trial. *Undersea Biomed Res* 1985;12(3):327–332.
39. Behnke A. *A review of physiologic and clinical data pertaining to decompression sickness*. United States Naval Medical Research Institute, 1947.
40. Benzinger T, Hornberger W, *Die Druckfallkrankheit der Höhenflieger*. No.34. Schriften der deutschen Akademie der Luftfahrtforschung, 1941.
41. Pilmanis AA, Meissner FW, Olson RM. Left ventricular gas emboli in six cases of altitude-induced decompression sickness. *Aviat Space Environ Med* 1996;67(11):1092–1096.
42. Piccard J. Aeroemphysema and the birth of gas bubbles. *Proc Staff Meet Mayo Clin* 1941;16:700–704.
43. Vann R, Gerth WA. Physiology of decompression sickness. *Hypobaric decompression sickness*. Brooks AFB, Texas: Proceedings of a workshop at the Armstrong Laboratory, 1992.
44. Vann R. Chapter 11: Mechanisms and risk of decompression. In: Bove AA, ed. *Diving medicine*. WB Saunders, 1997.
45. Van Liew H. *Bubble dynamics*. *Hypobaric decompression sickness*. Brooks AFB, Texas: Armstrong Laboratory, 1992.
46. Kumar KV, Waligora JM, Calkins DS. Threshold altitude resulting in decompression sickness. *Aviat Space Environ Med* 1990;61(8): 685–689.
47. Webb JT, Kannan N, Pilmanis AA. Gender not a factor for altitude decompression sickness risk. *Aviat Space Environ Med* 2003; 74(1):2–10.
48. Sheffield PJ. Flying after diving guidelines: a review. *Aviat Space Environ Med* 1990;61(12):1130–1138.
49. Dutka A, Francis TJ. Pathophysiology of decompression sickness. In: Bove AA, ed. *Diving medicine*. Philadelphia: WBSaunders:1997.
50. Harvey E, Barnes DK, McElroy AH, et al. Bubble formation in animals: I. Physical factors *J Cell Comp Physiol* 1944;24(1):1–22.
51. Webb JT, Fischer MD, Heaps CL, et al. Exercise-enhanced preoxygenation increases protection from decompression sickness. *Aviat Space Environ Med* 1996;67(7):618–624.
52. Balldin UI, Lundgren CE. Effects of immersion with the head above water on tissue nitrogen elimination in man. *Aerosp Med* 1972; 43(10):1101–1108.
53. Butler B. Cardiopulmonary effects of decompression bubbles. *Hypobaric decompression sickness*. Brooks AFB, Texas: Proceedings of a workshop at the Armstrong Laboratory; 1992.
54. Bove AA, Hallenbeck JM, Elliott DH. Circulatory responses to venous air embolism and decompression sickness in dogs. *Undersea Biomed Res* 1974;1(3):207–220.
55. Diesel DA, Ryles MT, Pilmanis AA, et al. Non-invasive measurement of pulmonary artery pressure in humans with simulated altitude-induced venous gas emboli. *Aviat Space Environ Med* 2002;73(2):128–133.
56. Chang JL, Albin MS, Bunegin L, et al. Analysis and comparison of venous air embolism detection methods. *Neurosurgery* 1980; 7(2):135–141.
57. Khan MA, Alkalay I, Suetsugu S, et al. Acute changes in lung mechanics following pulmonary emboli of various gases in dogs. *J Appl Physiol* 1972;33(6):774–777.
58. Harvey E, Whiteley AH, McElroy WD, et al. Bubble formation in animals II. Gas nuclei and their distribution in blood and tissues. *J Cell Comp Physiol* 1944;24:23–34.
59. Ring GC, Blum AS, Kurbatov T, et al. Size of microspheres passing through pulmonary circuit in the dog. *Am J Physiol* 1961;200: 1191–1196.
60. Philp RB. A review of blood changes associated with compression-decompression: relationship to decompression sickness. *Undersea Biomed Res* 1974;1(2):117–150.
61. Brubakk A, Vik A, Flook V. Gas bubbles and the lung. In: Lundgren MJ. ed. *The lung at depth*. Basel: Marcel Dekker Inc, 1999.
62. Harding R. DCS-experience outside North America. *Hypobaric decompression sickness*. Brooks AFB, Texas: Armstrong Laboratory, 1992.
63. Rice G, Anderson D. Altitude DCS following Naval altitude chamber operations (January 1996–October 2000, in *Aerospace Medical Association Scientific Meeting*, Reno, 2001. Abstract No.66.
64. Weien R Altitude decompression sickness: the US army experience. *Hypobaric decompression sickness.*. Brooks AFB, Texas: Armstrong Laboratory, 1992.
65. Baumgartner N, Weien RW Decompression sickness due to USAF altitude chamber exposure(1985–1987). *Hypobaric decompression sickness*. Brooks AFB, Texas: Armstrong Laboratory, 1990.
66. Kemper G USAF aircraft operations: DCS-mishaps.*Hypobaric decompression sickness*. Brooks AFB, Texas: Armstrong Laboratory, 1992.
67. Neubauer JC, Dixon JP, Herndon CM. Fatal pulmonary decompression sickness: a case report. *Aviat Space Environ Med* 1988; 59(12):1181–1184.
68. Bendrick GA, Ainscough MJ, Pilmanis AA, et al. Prevalence of decompression sickness among U−2 pilots. *Aviat Space Environ Med* 1996;67(3):199–206.
69. Haske TL, Pilmanis AA. Decompression sickness latency as a function of altitude to 25,000 feet. *Aviat Space Environ Med* 2002; 73(11):1059–1062.
70. Davis JC, Dunn JM, Gates GA, et al. Altitude decompression sickness: hyperbaric therapy results in 145 cases. *Aviat Space Environ Med* 1977;48(8):722–730.
71. Webb JT, Pilmanis AA. Altitude decompression sickness between 6858 and 9144 m following a 1-h prebreathe. *Aviat Space Environ Med* 2005;76(1):34–38.
72. Pilmanis AA, Petropoulos LJ, Kannan N, et al. Decompression sickness risk model: development and validation by 150 prospective hypobaric exposures. *Aviat Space Environ Med* 2004;75(9): 749–759.

73. Pilmanis AA, Webb JT, Kannan N, et al. The effect of repeated altitude exposures on the incidence of decompression sickness. *Aviat Space Environ Med* 2002;73(6):525–531.
74. Rice GM, Vacchiano CA, Moore JL Jr, et al. Incidence of decompression sickness in hypoxia training with and without 30-min O2 prebreathe. *Aviat Space Environ Med* 2003;74:56–61.
75. Pollock NW, Natoli MJ, Gerth WA, et al. Risk of decompression sickness during exposure to high cabin altitude after diving. *Aviat Space Environ Med* 2003;74(11):1163–1168.
76. Piwinski S, Cassingham R, Mills J, et al. Decompression sickness incidence over 63 months of hypobaric chamber operation. *Aviat Space Environ Med* 1986;57(11):1097–1101.
77. Weien RW, Baumgartner N. Altitude decompression sickness: hyperbaric therapy results in 528 cases. *Aviat Space Environ Med* 1990; 61(9):833–836.
78. Webb JT, Pilmanis AA, O'Connor RB. An abrupt zero-preoxygenation altitude threshold for decompression sickness symptoms. *Aviat Space Environ Med* 1998;69(4):335–340.
79. Webb JT, Krause KM, Pilmanis AA, et al. The effect of exposure to 35,000 ft on incidence of altitude decompression sickness. *Aviat Space Environ Med* 2001;72(6):509–512.
80. Webb JT, Pilmanis AA, Fischer MD, et al. Enhancement of preoxygenation for decompression sickness protection: effect of exercise duration. *Aviat Space Environ Med* 2002;73(12):1161–1166.
81. Webb JT, Pilmanis AA, Balldin UI. Altitude decompression sickness at 7620 m following prebreathe enhanced with exercise periods. *Aviat Space Environ Med* 2004;75(10):859–864.
82. Boothby WL, Lovelace WR, Benson OO. *Accumulated nitrogen elimination at rest and at work (walking on a treadmill).* NRC-report MAYO AERO MEDICAL UNIT USA, Rochester, MN November 1940.
83. Hankins TC, Webb JT, Neddo GC, et al. Test and evaluation of exercise-enhanced preoxygenation in U−2 operations. *Aviat Space Environ Med* 2000;71(8):822–826.
84. Gernhardt M, Conkin J, Foster PP, et al. Design of a 2-hour prebreathe protocol for space walks from the international space station. Abstract 43. *Aerospace Medical Association 70th Annual Scientific Meeting 2000*. Houston, May 14–18, 2000.
85. Webb JT, Pilmanis AA, Balldin UI, et al. Altitude decompression sickness susceptibility: influence of anthropometric and physiologic variables. *Aviat Space Environ Med* 2005;76(6):547–551.
86. Macmillan A. Decompression illness and hyperbaric therapy. In: Ernsting J, Nicholson A, et al. eds. Aviation Medicine. Butterworth-Heinemann, 1999.
87. Motley H, Chinn HI, Odell FA. Studies on bends *J Aviat Med* 1945;16:210–234.
88. Smith H. The effect of anoxia on the incidence of decompression sickness at 35′000 feet. In: *Report to Director of Medical Sciences (Air)*. Number 2. Regina: Clinical Investigation Unit RCAF, Jan. 1943.
89. Smith H, The effect of anoxia on the incidence of decompression sickness at 35′000 feet. In: *Report to Director of medical sciences (Air)*. Number 2. Regina: Clinical Investigation Unit RCAF, 1943.
90. Burkhardt W, Thometz AF, Ivy AC. *The effect of deliberate hyperventilation on the incidence of "intolerable" cases of bends and chokes.* 1944.
91. Hodes R, Larrabee MG. The relation between alveolar carbon dioxide tension and susceptibility to decompression sickness. *Am J Physiol* 1946;147:603–615.
92. Stewart C, Smith HW, McAlpine HA, et al. *The incidence of decompression sickness on consecutive daily ascents to 35′000 ft*. Number 2. Regina: Clinical Investigation Unit RCAF, 1942.
93. Warwick O. *The apparent relationship of fluid balance to the incidence of decompression sickness*. Number 2. Regina: Clinical Investigation Unit RCAF, 1942.
94. Warwick O. *Further studies on the relationship of fluid intake and output to the incidence of decompression sickness.* Number 1. Halifax: Flying personnel Medical Section, "Y" Depot RCAF, 1943.
95. Balldin UI, Pilmanis AA, Webb JT. The effect of simulated weightlessness on hypobaric decompression sickness. *Aviat Space Environ Med* 2002;73(8):773–778.
96. Webb JT, Beckstrand DP, Pilmanis AA, et al. Decompression sickness during simulated extravehicular activity: ambulation vs. non-ambulation. *Aviat Space Environ Med* 2005;76(8):778–781.
97. Moon R. Patent foramen ovale (PFO) and decompression illness in space. In *Aerospace Medical Association Meeting*. Houston, 2000
98. Bove A, Risk of decompression sickness with patent foramen ovale. *Undersea Hyperb Med* 1998;25(3):175–178.
99. Knauth M, Ries S, Pohlmann S, et al. Cohort study of multiple brain lesions in sport divers: role of a patent foramen ovale. *Br Med J* 1997;314(7082):701–705.
100. Hagen PT, Scholz DG, Edwards WD. Incidence and size of patent foramen ovale during the first 10 decades of life: an autopsy study of 965 normal hearts. *Mayo Clin Proc* 1984;59(1):17–20.
101. United States Navy. *United States navy diving manual*. NAVSEA 0910-LP−708−8000. USN; 1999.
102. Lovelace WR, Gagge AP. Aero medical aspects of cabin pressurization for military and commercial aircraft. *J Aeronaut Sci* 1946; 13(3):143–150.
103. Webb JT, Pilmanis AA, Kannan N, et al. The effect of staged decompression while breathing 100% oxygen on altitude decompression sickness. *Aviat Space Environ Med* 2000;71(7):692–698.
104. Webb J, Pilmanis AA, Balldin U. The effect of a 60 min air breathing break during preoxygenation on altitude decompression sickness risk. *Aerospace Medical Association scientific program*. Orlando: Aviation Space & Environmental Medicine, 2006.
105. Golding FC, Griffiths P, Hempleman HV, et al. Decompression sickness during construction of the Dartford Tunnel. *Br J Ind Med* 1960;17:167–180.
106. Donnell AJ, Morgan CP. Successful use of the recompression chamber in severe decompression sickness with neurocirculatory collapse. *Aerosp Med* 1960;31:1004.
107. Francis J The classification of decompression illness. *Hypobaric decompression sickness*. San Antonio, Brooks Air Force Base, Texas: Aerospace Medical Association and Undersea & Hyperbaric Medicine Society, 1992.
108. Balldin UI, Pilmanis AA, Webb JT. Pulmonary decompression sickness at altitude: early symptoms and circulating gas emboli. *Aviat Space Environ Med* 2002;73(10):996–999.
109. Balldin UI, Pilmanis AA, Webb JT. Central nervous system decompression sickness and venous gas emboli in hypobaric conditions. *Aviat Space Environ Med* 2004;75(11):969–972.
110. Ryles MT, Pilmanis AA. The initial signs and symptoms of altitude decompression sickness. *Aviat Space Environ Med* 1996;67(10): 983–989.
111. Rudge FW, Stone JA. The use of the pressure cuff test in the diagnosis of decompression sickness. *Aviat Space Environ Med* 1991; 62(3):266–267.
112. Clark J The neurologic evaluation of decompression sickness. *Hypobaric decompression sickness*. San Antonio, Brooks Air Force Base, Texas.: Aerospace Medical Association and Undersea & Hyperbaric Medicine Society, 1992.
113. Rudge FW. Variations in the presentation of altitude-induced chokes. *Aviat Space Environ Med* 1995;66(12):1185–1187.
114. Conkin J, Pilmanis AA, Webb JT. *Case descriptions and observations about cutis marmorata from hypobaric decompressions.* NASA, 2002.
115. Macmillan A. Sub-atmospheric decompression sickness. In: Ernsting J, Nicholson AN, Rainford DJ, eds. *Aviation medicine*. Butterworth-Heinemann, 1999.
116. Hodgson CJ, Davis JC, Randolph CL Jr, et al. Seven year follow-up x-ray survey for bone changes in low pressure chamber operators. *Aerosp Med* 1968;39(4):417–421.
117. Muehlberger PM, Pilmanis AA, Webb JT, et al. Altitude decompression sickness symptom resolution during descent to ground level. *Aviat Space Environ Med* 2004;75(6):496–499.

118. Downey VM, Worley TW, Hackworth R, et al. Studies on bubbles in human serum under increased and decreased atmospheric pressures. *Aerosp Med* 1963:116–118.
119. Leverett S, Bitter HL, McIver RG. *Studies in decompression sickness: circulatory and respiratory changes associated with decompression sickness in anesthetized dogs*. Brooks Air Force Base, San Antonio, Texas: United States Air Force School of Aerospace Medicine, 1963.
120. Krause KM, Pilmanis AA. The effectiveness of ground level oxygen treatment for altitude decompression sickness in human research subjects. *Aviat Space Environ Med* 2000;71(2):115–118.
121. Jooste PL, Wolfswinkel JM, Schoeman JJ, et al. Epileptic-type convulsions and magnesium deficiency. *Aviat Space Environ Med* 1979;50:734–735.
122. Webb J. *Aerospace physiology reference*. USAFSAM, 2007.
123. Goodman M, Workman RD. U.S.N.E.D. Unit. AFP 160–5 Chapter 1–5, *Minimal recompression oxygen breathing approach to treatment of decompression sickness in divers and aviators.* Washington, DC: Government Printing Office, 1965.
124. Catron PW, Flynn ET Jr. Adjuvant drug therapy for decompression sickness: a review. *Undersea Biomed Res* 1982;9(2):161–174.
125. Spadaro M, Moon RE, Fracia PJ, et al. Life threatening pulmonary thromboembolism in neurological decompression illness. *Undersea Biomed Res* 1992;19:41–42.
126. Moses J, David MT, Stevenson KM, et al Pulmonary embolism as a sequela to neurological decompression sickness. *Pressure* 1998; 28:8–9.
127. Reeves E, Workman RD. Use of heparin for the therapeutic-prophylactic treatment of decompression sickness. *Aerosp Med* 1971;42(1):20–23.
128. Inwood M. Experimental evidence in support of the hypothesis that intravascular bubbles activate the hemostatic process. *Symposium on blood-bubble interactions in decompression sickness*. Defence and Civil Institute of Environmental Medicine, 1973.
129. Evans DE, Catron PW, McDermott JJ, et al. Effect of lidocaine after experimental cerebral ischemia induced by air embolism. *J Neurosurg* 1989;70(1):97–102.
130. Herren JI, Kunzelman KS, Vocelka C, et al. Angiographic and histological evaluation of porcine retinal vascular damage and protection with perfluorocarbons after massive air embolism. *Stroke* 1998;29(11):2396–2403.
131. Lynch PR, Krasner LJ, Vinciquerra T, et al. Effects of intravenous perfluorocarbon and oxygen breathing on acute decompression sickness in the hamster. *Undersea Biomed Res* 1989;16(4):275–281.
132. Novotny JA, Bridgewater BJ, Himm JF, et al. Quantifying the effect of intravascular perfluorocarbon on xenon elimination from canine muscle. *J Appl Physiol* 1993;74(3):1356–1360.
133. Spiess BD, McCarthy RJ, Tuman KJ, et al. Treatment of decompression sickness with a perfluorocarbon emulsion (FC−43). *Undersea Biomed Res* 1988;15(1):31–37.
134. Stoney WS, Alford WC, Burns GR, et al. Air embolism and other accidents using pump oxygenators. *Ann Thorac Surg* 1980; 29(4):336–340.
135. Pilmanis A. Decompression hazards at very high altitudes. *Raising the operational ceiling*. Brooks AFB, Texas: Proceedings of a workshop at the Armstrong Laboratory, 1995.

SUGGESTED READINGS

Adler HF. *Dysbarism. Aeromedical Review 1B64.*. Brooks Air Force Base, Texas: United States Air Force School of Aerospace Medicine, 1964.

Bennett P, Elliotts DH. In: Brubakk A, Neuman T, eds. *Physiology and medicine of diving*, 5th ed. Baltimore: WB Saunders, 2002.

Bove AA, Davis JC. *Diving medicine*, 4th ed. Philadelphia: WBSaunders, 2004.

Clamann HG. Decompression sickness. In: Randel HW, ed. *Aerospace medicine*. Baltimore: Williams & Wilkins, 1971.

Davis JC, Hunt TK, eds. *Hyperbaric oxygen therapy*. Bethesda: Undersea Medical Society, 1977.

Engle E, Lott A. *Man in flight: biomedical achievements in aerospace*. Annapolis: Leeward Publications, 1979.

Folarin VA. *Flight surgeon's checklist*, 6th ed. Society of USAF flight surgeons, 2000.

Foster PP, Boriek AM, Butler BD. Patent foramen ovale and paradoxical systemic embolism: a bibliographic review [Review]. *Aviat Space Environ Med* 2003;74(6 Pt 2):B1–64.

Fryer DI. *Subatmospheric decompression sickness in man*. Slough: Technovision Services. The Advisory Group for Aerospace Research and Development, NATO, 1969.

Gradwell D, Ernsting J. *Aviation medicine*, 4th ed. Butterworth-Heinemann, 2007.

Gray JS, Mahady SCF, Masland RL. Studies on altitude decompression sickness III. The effects of denitrogenation. *J Aviat Med* 1946;17:606.

Green RD, Leitch DR. Twenty years of treating decompression sickness. *Aviat Space Environ Med* 1987;58:362–366.

Kindwall EP, ed. *Hyperbaric medicine practice*. Flagstaff: Best Publishing Company, 1994.

Lundgren CE, Miller JN. *The lung at depth. Lung biology in health and disease*. Vol. 132. New York: Marcel Dekker Inc, 1999.

Malconian MK, Rock P, Devine J. Operation Everest II: altitude decompression sickness during repeated altitude exposure. *Aviat Space Environ Med* 1987;58:679–682.

Pilmanis AA. *Hypobaric decompression sickness*. Brooks AFB, Texas: Proceedings of a workshop at the Armstrong Laboratory, 1990.

Pilmanis AA, Petropoulos L, Kannan N. Decompression sickness risk model: development and validation by 150 prospective hypobaric exposures. *Aviat Space Environ Med* 2004;75:749–759.

Pilmanis AA, Sears WJ. *Raising the operational ceiling*. Brooks AFB, Texas: Proceedings of a workshop at the Armstrong Laboratory, 1995.

Saary MJ, Gray JW. A review of the relationship between patent foramen ovale and type II decompression sickness [Review]. *Aviat Space Environ Med* 2001;72(12):1113–1120.

Surgeon General, USAF. *German aviation medicine, World War II*. Vols. I and II. Department of the Air Force. US Government Printing Office. 1950.

Thalmann ED. Principles of U.S. Navy recompression treatment for decompression sickness. In: Moon RE, Sheffield PJ, eds. *Treatment of decompression illness*. Rockville: Undersea and Hyperbaric Medical Society, Proceedings of the forty-fifth Undersea and Hyperbaric Medical Society Workshop, 1996.

USAF *Aerospace physiology handbook*. USAFSAM, AFP 160–5 Chapter 1–5, 2007. Access to the ADRAC website: the user can register at http://biodyn1.wpafb.af.mil/altitude/login/Login.aspx?ReturnUrl=%2faltitude%2fDefault.aspx, and may be granted access privileges to the use of the ADRAC model.

Naval Aerospace Medical Institute. Physiology of flight.1991 bubble related diseases. *United States Naval Flight Surgeon's Manual*, 3rd ed. http://www.vnh.org/FSManual/01/09BubbleRelatedDisease.html.

Ward MP, Milledge JS, West JB. *High altitude medicine and physiology*, 3rd ed. London: Arnold, 2000.

Webb JT, Kannan N, Pilmanis AA. Gender not a factor for altitude decompression sickness risk. *Aviat Space Environ Med* 2003;74(1): 2–10.

West JB. *High life*. American Physiological Society, Oxford University Press, 1998.

Wilmshurst P, Edge CJ, Bryson P. Long-term adverse effects of scuba diving. *Lancet* 1995;346:384.

CHAPTER 4

Human Response to Acceleration

Robert D. Banks, James W. Brinkley, Richard Allnutt, and Richard M. Harding

> The most reliable instrument for measuring the varied effects of dynamic force on man is man.
>
> —*Colonel John Paul Stapp*

> The first principle is that you must not fool yourself and you're the easiest person to fool.
>
> —*Richard Feynman*

INTRODUCTION

Acceleration is the rate of change of velocity. The human response to acceleration depends on magnitude, direction, and duration. The response may be physiological and involve homeostasis during accelerations of low magnitude and long duration. Or it may involve physical injury when the acceleration is high and of short duration. These two general outcomes characterize the way human response to acceleration has been considered, studied, and analyzed.

Low-magnitude, long-duration acceleration involving humans has been termed *sustained acceleration*. High-magnitude, short-duration acceleration has been termed *impact* or *transient acceleration*. In this chapter, we consider the effects of both sustained and impact acceleration on humans and some of the protective strategies associated with each. Because sustained acceleration is encountered by pilots in flight and the major threat is incapacitation, the aim of protection is to prevent a crash and enhance flying ability. Because transient acceleration is encountered during flight operations, escape, or during a crash, the aim of protection is to maintain function, reduce injury potential, and enhance survivability.

These two areas employ very different research methods: one involves mainly human centrifuges and the other, impact tracks and towers. Both approaches have limitations in their ability to simulate real-world events. Models, based on appropriate research, have been developed according to the principles of Newtonian mechanics. We begin with a review of these principles.

Newton's Laws

Newton's first law states that a body that is at rest or in motion will remain in that state unless acted upon by a force. A force is a push or pull. For example, an aircraft in straight and level flight is without acceleration if the forces acting on the aircraft are in balance. Similarly, occupants of the aircraft are without acceleration, although they will experience the force of gravity by virtue of lift of the wings.

If an aircraft follows a curving path, such as during a banked turn or upward pitch, a force must act on the aircraft to alter its path (in this case, forces due to lift). In Figure 4-1, the aircraft pitches up due to the forces of lift.

Occupants inside the aircraft also follow Newton's first law and therefore follow a straight path at a constant velocity unless acted upon by a force. During a banked turn or upward pitch, this force is exerted on the occupant by the seat and floor of the aircraft as illustrated in Figure 4-1.

In Figure 4-2, we illustrate the case of an aircraft pitching down. In this example, the occupant is experiencing a fall to Earth and is also being pulled down by the lap and shoulder belts.

When an aircraft impacts the ground during a crash, the velocity of the aircraft changes abruptly and the aircraft

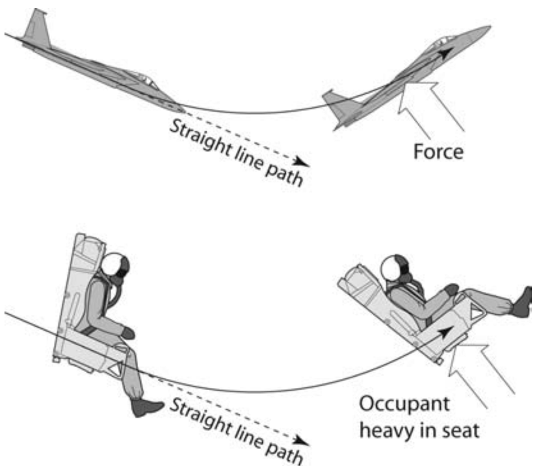


FIGURE 4-1 Newton's first law. The aircraft will continue in a straight path unless acted upon by an unbalanced force. When the aircraft follows a curving path, the unbalanced force is due to lift. The occupant will also follow a straight path unless acted upon by an unbalanced force. In this case, the force is the aircraft acting upwards on the pilot (*Source:* John Martini, BRC).

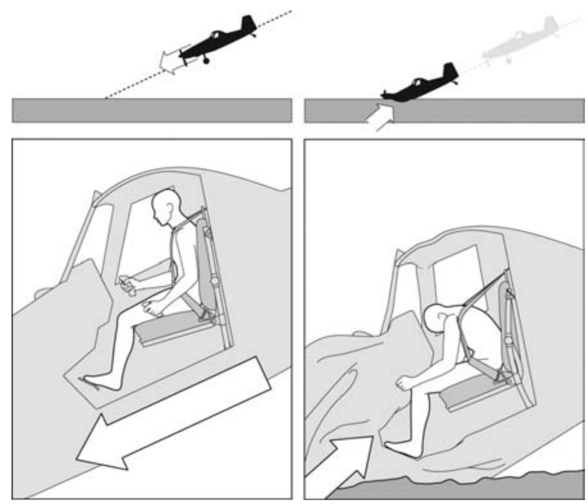


FIGURE 4-3 Newton's first law applied to an occupant during a crash. The occupant will continue at the precrash velocity during the event until encountering objects forward of the initial position. In this case, these objects include the restraints, controls, and the instrument panel. As seen from within the aircraft, occupant motion appears to be forward (*Source:* John Martini, BRC).

experiences deceleration. In accordance with Newton's first law, the occupants of the aircraft will continue at their preimpact velocities until they contact interior aircraft structures that are slowing. In a frontal impact, the first such structure is the restraint system. The next structure will be the instrument panel or control column. Figure 4-3 shows a pilot immediately before the aircraft contacts water. As depicted, during the impact event, the pilot experiences motion within the cockpit interior and contacts forward structures.

Newton's second law relates force and acceleration, and is expressed as:

$$F = ma \qquad [1]$$

where F = force, m = mass, a = acceleration.

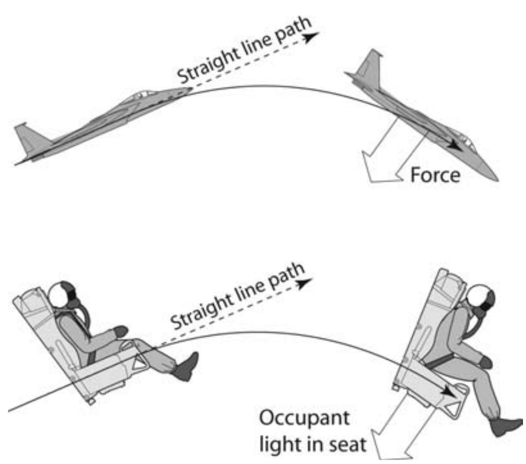


FIGURE 4-2 Newton's first law applied to an occupant in flight. The force acting on the occupant is downward through the lap and shoulder restraints. The occupant will tend to rise out of the seat (*Source:* John Martini, BRC).

We can see from Newton's second law that when acceleration increases so does force, and *vice versa*. When a force is applied to an occupant through the seat or restraint, the occupant experiences both acceleration and force. In the case of frontal impact with terrain, the occupant experiences acceleration and force due to contact with the restraints and forward cockpit structures.

Newton's third law states that any force exerted by one body on another is countered by an equal and oppositely directed force. Because colliding objects usually have different masses, the resulting accelerations will not be the same (Newton's second law).

Understanding G

The acceleration due to gravity is the same (constant) anywhere on the surface of a planet although it decreases with increasing distance from the center. On Earth, this constant is designated "g" and has the value of approximately 9.81 meters/second squared (m/s^2). The force that an object exerts on the Earth's surface (weight) depends on the mass of the object, but will be the same anywhere on the Earth's surface for that mass.

The situation is different on other planets. On our moon, for example, acceleration due to gravity is only 1.62 m/s^2 and an object will fall to the lunar surface with less acceleration than on Earth. Similarly, the weight of an object on the moon's surface is less than that of the same object on Earth. A person who weighs 78 kilograms (kg) on Earth will weigh only 13 kg on the moon.

Gravity also affects objects in space that are close to the Earth. Gravity causes spacecraft and their occupants to fall toward the Earth. Spacecraft that have achieved orbital velocity during launch (8 km/s) circle the Earth. Because the Earth's surface curves away from their path (being round), the spacecraft and crewmembers cannot close the distance to the surface and so remain in semiperpetual freefall. The "weightlessness" of Earth's orbit is not the absence of gravity; it is a condition of frictionless freefall.

"G" is a measure of the acceleration experienced by a person as a result of a force. Alternatively, it can be regarded as a measure of the force experienced by a person due to acceleration. It is expressed in terms of multiples of the Earth's gravitational acceleration. One G is experienced during acceleration of 9.81 m/s^2(g).

The relationship of G and acceleration can therefore be expressed as:

$$G = a/g \quad [2]$$

Because both "a" and "g" have units of m/s^2, and they are divided, the units cancel and G is without units—it is a ratio.

As stated, the G coefficient relates to force. For example, a pilot weighing 70 kg on Earth who is subject to an in-flight acceleration of 3 G (and is supported by the seat and restraints), will experience a force that is three times his weight, or 210 kg. It is often more practical to discuss G instead of force or acceleration because force measurements vary with pilot mass, but acceleration does not. *Acceleration* is convenient to consider in terms of multiples of gravity, and is the term used by aircrew and flight surgeons in the aviation community.

Vectors and Nomenclature

Any quantity that has the properties of magnitude and direction is called a *vector*. Acceleration, velocity, and force are examples of vectors. G is also a vector. Vectors can be analyzed mathematically using trigonometry. Vectors are described on plots that demonstrate their magnitude and direction. These plots are defined by three mutually orthogonal linear axes: x, y, and z. In aerospace medicine, these plots are considered to be aligned with a forward-facing crewmember as depicted in Figure 4-4.

There has been considerable disagreement about both the conventional placement of axes, and the use of symbols and terms. Basic differences exist between the engineering and aeromedical communities, and within each of these groups. Attempts to achieve uniformity have had mixed results. For example, the Advisory Group for Aerospace Research and Development (AGARD) standard for human acceleration differs from the AGARD standard for aircraft design (in which the z-acceleration axis is reversed and positive downward). It also differs from previous editions of this textbook, which differ from one another. Needless to say, when reading literature involving acceleration it is important to understand clearly the author's use of these terms and symbols.

To be consistent with the AGARD standard (1), the Table of Equivalents for Acceleration Terminology (2), the Aviation Space and Environmental Medicine Standard (3), and the majority of the Aerospace Medicine literature, the positive direction of each of these axes is here described by "the left-hand rule." That is, the x-axis dimension is an arrow with the positive direction forward, the y-axis dimension has the positive direction rightward, and the z-axis dimension has the positive dimension upward. This is depicted in Figure 4-4.

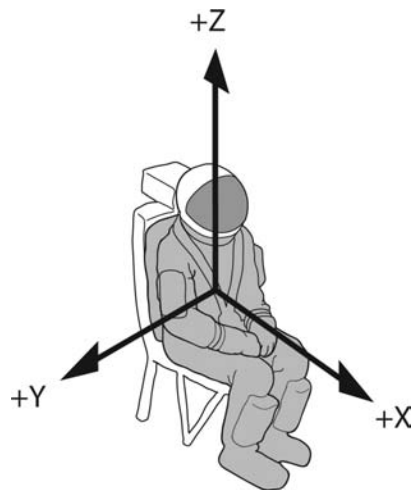


FIGURE 4-4 An axial diagram of the human coordinate system for linear motion. This convention is referred to as the *left-hand rule* because the placement of the axes mimic a left hand with the index finger pointed forward, the thumb pointed up, and the middle finger directed to the right (*Source:* John Martini, BRC).

Aircraft acceleration vectors can be described using this convention. If an aircraft accelerates forward, in the positive direction, the acceleration is denoted by "$+a_x$". If the direction of aircraft acceleration is upward, the designation $+a_z$ is used. If the direction is to the right, $+a_y$ is used. These symbols are included in the first column of Table 4-1.

The positive direction of the G of an occupant in response to aircraft acceleration is aligned with a. Therefore, when $+a_x$ is experienced by the aircraft, a forward-facing occupant experiences $+G_x$. Otherwise stated, $+G_x$ is caused by acceleration of the seat forward and results in pressure between the seatback and the pilot's back. $+G_y$ is caused by acceleration of the seat toward the right and results in pressure between the left hip and the left armrest. Positive-G_z is caused by acceleration of the seat upward and results in pressure between the buttocks and the seat pan. These conventions and their counterparts are summarized in Table 4-1. In column 3,

TABLE 4-1

Directions of Acceleration and Use of Terms

Acceleration	*Cause G*	*Description*
$+a_x$	$+G_x$	"Step on the gas"
$-a_x$	$-G_x$	"Step on the brakes"
$+a_y$	$+G_y$	Pressure against left arm rest
$-a_y$	$-G_y$	Pressure against right arm rest
$+a_z$	$+G_z$	Heavy in the seat
$-a_z$	$-G_z$	Light in the seat

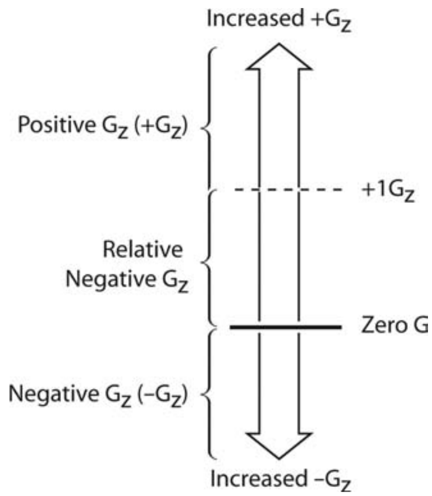


FIGURE 4-5 Vertical accelerations greater than $+1$ G_z are termed *positive-*G_z ($+G_z$). Any $+G_z$ less than $+1$ G_z is termed *relative* $-G_z$. Any G_z less than zero-G_z is termed *negative-*G_z ($-G_z$) (*Source:* John Martini, BRC).

we have included phrases that may aid in understanding these conventions. The symbol "G", without a subscript letter or prefix symbol, is used when the direction is not specified.

Another source of confusion is associated with the +1 G of gravity. An aircraft at rest on the Earth, or in straight and level flight, experiences +1 G_z, and yet there is no acceleration. Therefore, the zero-acceleration reference point in the z-direction is +1 G_z because of gravity. Because any G_z less than +1 G_z is *relatively negative*, in terms of the effect on an upright human, we use the term *relative* $-G_z$ to describe G_z stress that is less than +1 G_z, but greater than zero-G_z. When G_z is less than zero-G_z, the expression "negative-G" or "–G_z" is used. Confusion can occur when thinking of less than +1 G_z and greater than zero-G_z. Although this is technically $+G_z$, physiologically, the body responds as if it is $-G_z$ because the autonomic nervous system is adapted to gravity. Figure 4-5 illustrates this definition.

Frames of Reference

To have proper meaning, the orthogonal linear axes used to describe vectors must be defined according to a "frame of reference." For example, a person sitting on a train traveling at a constant velocity of 100 Kmph would perceive no speed inside the train and that would be indicated on a vector plot referenced to the inside of the train. An observer positioned in an alternate frame of reference, such as outside the train at a station, would see the person in the train speeding past at 100 kmph, and a vector plot referenced to the station would reflect this velocity. Although describing the same event, the vectors would look quite different because of the different frames of reference.

Any vector, including force, velocity, and acceleration (or G) depends on the frame of reference selected. Sustained acceleration is usually considered within the reference frame of the aircraft interior and occupant space. Transient acceleration is often considered within the reference frame of the Earth.

G is measured using an instrument called an *accelerometer*, or *G-meter*. Many aircraft have G-meters mounted on the aircraft and positioned in the cockpit, where they can be seen by the pilots. The G-meter is calibrated to measure acceleration in the aircraft reference frame (a_z in units of G_z). Similarly, human centrifuges, used to create G on Earth, often have accelerometers mounted near the occupant seat.

PHYSIOLOGY OF SUSTAINED ACCELERATION

Sustained acceleration occurs during normal and aerobatic flight. Because most aircraft maneuvers (such as pitch and banked turns) expose seated occupants to predominantly $+G_z$, the effects of $+G_z$ on humans has received most of research attention. Negative-G_z has received much less attention, most of it during and shortly after World War II. G_x and zero-G are most relevant to space flight. G_y has only begun to receive research attention with the development of vectored thrust fighters.

This section describes the effects of sustained G in present-day aviation and space flight. Countermeasures are described and limitations in current research are discussed. The need for a revised model of $+G_z$ tolerance is suggested.

Relevant Mechanics

Humans respond physiologically to G. When an aircraft follows a curving path, the velocity changes continuously along the curve (being a vector, although speed may remain constant) and the aircraft experiences acceleration. The acceleration of the aircraft depends on the velocity of the aircraft and the radius of the turn. This is expressed as:

$$a = v^2/r \qquad [3]$$

where v = velocity, r = radius of the turn.

If the aircraft occupants are "fixed" to the aircraft, they experience the same acceleration, which is expressed as:

$$G = v^2/rg \qquad [4]$$

When an occupant experiences $+G_z$, the associated force is felt as increasing pressure of the buttocks against the surface of the seat. The occupant experiences "heaviness," and activities, such as lifting an arm, will be more difficult. When relative $-G_z$ is experienced, there is a reduction in pressure on the buttocks and the occupant may feel a rise off the seat. As $-G_z$ increases, pressure of the shoulder and lap restraints is experienced. Ultimately, the occupant may feel suspended by the shoulders and have the sensation of being inverted.

Some aircraft, including civilian aerobatic and military aircraft, are capable of executing large pitch changes at relatively high velocities and can therefore generate high G_z. The magnitude and duration of G_z that an aircraft generates depends on its structural strength and thrust.

Incidentally, Equation 3 can be used to calculate orbital velocity. In stable circular orbit, the acceleration of gravity is equal and opposite to the acceleration due to radius of turn. With a low-Earth orbital radius of 6,700 km, it is easy to show that the turn velocity necessary to create 1 G in opposition to the 1 G of gravity is approximately 8 km/s, which is the low-Earth orbital velocity previously mentioned. This orbital balance of acceleration vectors is a special and important case of weightlessness. Both the freefall concept and the acceleration balance concept are useful and correct in understanding orbital weightlessness.

The Fluid Model

When force is applied to fluid in a constrained volume, the pressure within increases. Pressure is a measure of force (per unit area) transmitted by fluids. For example, squeezing a filled plastic water bottle increases the pressure of the water inside the bottle. If the top is off, the increased water pressure compels the water to squirt out against the constraint of gravity and the resistance of the opening. Similarly, heart contraction during systole increases the pressure within the left ventricle and compels high-pressure blood to open the aortic valve and flow into the aorta.

On Earth, the force acting on a fluid at any depth varies with the weight of the fluid above, a principle of hydrostatics. Therefore, pressure increases with increased depth, a fact well known to divers. Referring to the depiction of the column of fluid in Figure 4-6, we expect the pressure of fluid to be less at point A than at point B because there is no fluid *above* point A. Because fluids are freely mobile, and have no internal rigid structure, pressure is transmitted within the fluid according to Pascal's principle (which states that a change in pressure at any point in a fluid is transmitted to every part of the fluid).

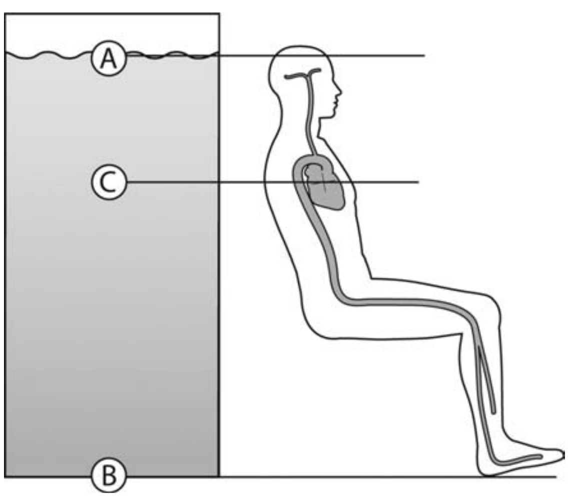


FIGURE 4-6 Hydrostatic blood pressure. A seated human figure is depicted next to a fluid-filled container. The hydrostatic pressure of the fluid is zero at the top of the container (**A**), and maximum at the bottom (**B**). The pressure is intermediate at point C, which is located between A and B. These principles apply equally to the fluids of the human figure seated to the right (*Source:* John Martini, BRC).

Hydrostatic principles apply to all fluids in the body, including the pericardial, pleural, abdominal, and cerebrospinal fluids, and both venous and arterial vascular systems. To the right of the water column in Figure 4-6, we present a seated upright human, and depict the continuous fluid column (cardiovascular system) that extends from the scalp to the feet. Ignoring any pressure generated by the heart, and considering only the hydrostatic pressure of the fluid column, blood pressure at level A is zero, because there is almost no blood above. Blood pressure at the feet (level B) is greatest and equal to the weight of the fluid above. At level C, blood pressure measured at the heart, is intermediate. This component of blood pressure is termed the *hydrostatic* pressure component.

Pressure due to contraction of the heart adds to the hydrostatic component of blood pressure. If we consider left ventricular contraction during systole, the force applied to the contained blood by cardiac muscle increases intraventricular blood pressure until the aortic valve opens. The increased blood pressure is then transmitted to the aorta and into the arterial system according to Pascal's principle. This component of blood pressure is termed the *dynamic* pressure component.

Total blood pressure is the sum of the dynamic and hydrostatic pressures. The measured systolic blood pressure at the heart level of a young healthy adult is typically approximately 120 mm Hg and is the sum of the two blood pressure components. Measurements taken at other vertical locations (e.g., the ankle) will be different.

Numerical estimates of hydrostatic blood pressure can be made using Equation 5, which states:

$$p = \rho g z \qquad [5]$$

where p = hydrostatic pressure, ρ = blood fluid density, z = vertical depth of fluid.

For a specific gravity of blood of 1.06, and after converting the units of p from Pascals to millimeters of mercury (mm Hg), Equation 5 becomes:

$$p = 0.78z \qquad [6]$$

where p is in mm Hg, and z is in cm.

Equation 6 can be used to estimate the hydrostatic component of blood pressure at different vertical fluid column depths on Earth ($+1\ G_Z$). For example, if the vertical distance from the aortic valve to the top of the head is 38 cm, Equation 6 predicts that the hydrostatic pressure at the aortic valve in an upright person is approximately 30 mm Hg (0.78×38).

As G increases, the apparent weight (force) of any object increases directly, and this applies equally to fluids. Under increased G, Equation 6 becomes:

$$p = 0.78zG \qquad [7]$$

Equation 7 can be used to predict G-tolerance, if physiological compensation is not considered. For example, an individual with a vertical fluid distance of 38 cm from the aortic valve to near the top of the head, and having a systolic blood pressure

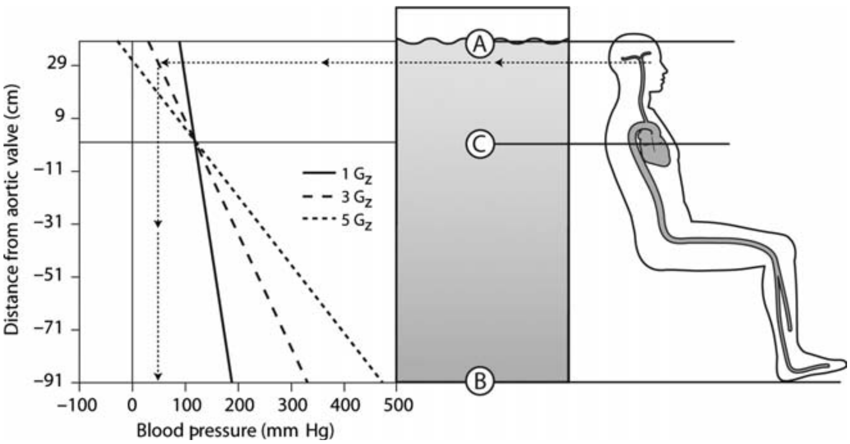
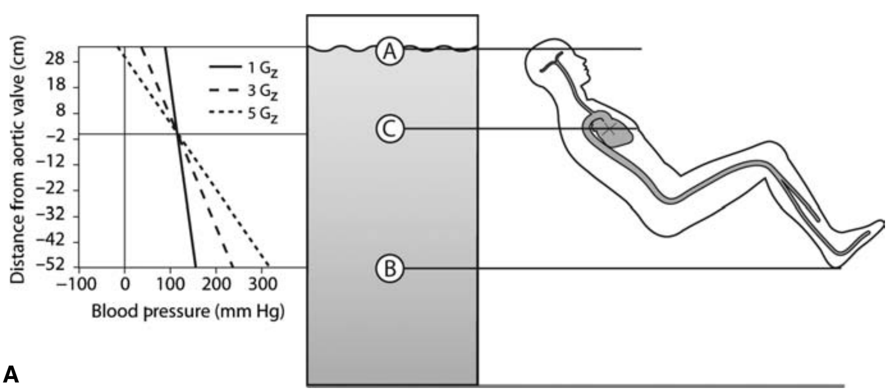


FIGURE 4-7 The estimated blood pressures are plotted next to a depiction of a seated human figure using Equations 6 and 7 (assuming a heart-level systolic blood pressure of 120 mm Hg and a 50% average male). To determine the blood pressure at any vertical location, a horizontal line can be run toward the left to the straight line plot of +Gz. The pressure is read directly below on the horizontal axis. The arrowed line provides an example of how to estimate the blood pressure at eye-level during exposure to +3 G_z. Note the high blood pressures in the lower extremities and predictions of head-level blood pressures at +5 G_z that are less than atmospheric (*Source:* John Martini, BRC).

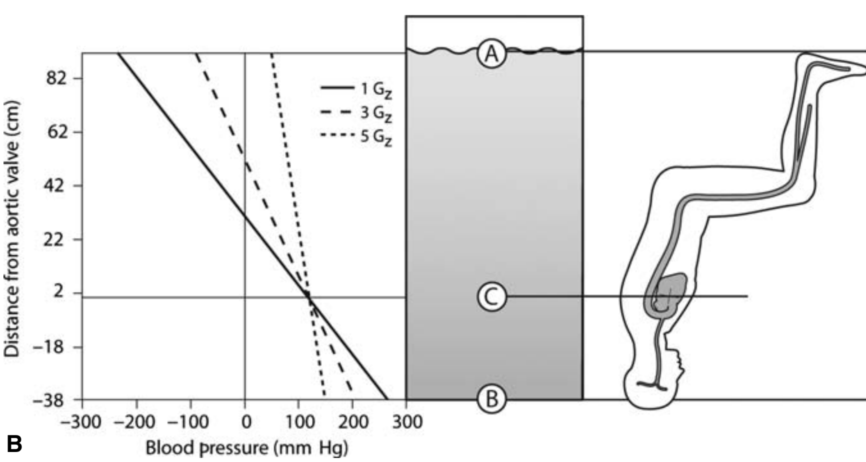
at the aortic valve of 120 mm Hg, would be expected to have zero systolic blood flow near the vertex at approximately +4 G_z [Equation 7: 120 mm Hg = 0.78(38)(4.0)]. This is a point above which the dynamic systolic blood pressure is unable to oppose the hydrostatic component of the blood. Consequently blood flow to the upper brain would cease.

Equation 7 can also be used to estimate blood pressures at other locations. Figure 4-7 shows the person seated upright as depicted previously in Figure 4-6. To the left of the human figure are plots of systolic blood pressures versus distance from the aortic valve based on Equations 6 and 7. There are three plots depicted: +1 G_z, +3 G_z, and +5 G_z, and they are based on the approximate dimensions of a 50% average male. Any estimates, using this simple model, will vary with individuals of different sizes. Note the very high blood pressures in the lower extremities at +5 G_z. Similarly, pressures at head level are predicted to be less than atmospheric pressure at +5 G_z. Once again, the underlying assumption is a heart-level systolic blood pressure of 120 mm Hg.

Equation 7 can be used for other postural orientations such as reclined or inverted. Figure 4-8A depicts the expected blood pressures for a seated reclined individual. Because of the reclined posture, the vertical heart-to-brain distance is decreased, and the hydrostatic blood pressure component is less. Positive-G_z tolerance is predictably



A



B

FIGURE 4-8 **A:** The estimated systolic blood pressures when the seated individual is reclined during +1 G_z, +3 G_z and +5 G_z exposure. By reclining the seatback, the vertical dimension of the hydrostatic column is reduced and hydrostatic pressure above the heart is reduced. Positive-G_z tolerance is predictably improved (*Source:* John Martini, BRC). **B:** The estimated systolic blood pressures when the seated individual is exposed to −1 G_z, −3 G_z and −5 G_z (inverted). This posture depicts increased levels of −G_z. Note the very high predicted head-level systolic blood pressures (*Source:* John Martini, BRC).

increased. Figure 4-8B demonstrates the effect of inversion, and also the very high head-level blood pressures that can be experienced during $-G_z$.

These predictions agree well with human studies that show a head-level reduction of blood pressure of approximately 30 mm Hg per change of each 1 G (4).

Blood pressure at the head is further lowered if circulating blood volume is reduced. When blood pressure increases during increased $+G_z$, as it does in the lower (dependent) areas of the body (Figure 4-7), stretching of tissues occurs. As a result of stretching of tissues in the abdomen and lower extremities, a portion of the circulating blood volume becomes unavailable for circulation.

Individual variations in heart-to-brain distances, and differences in blood pressures at the aortic valve, will change these predictions. Therefore, people with smaller vertical dimensions when upright will have an advantage tolerating $+G_z$ when compared to taller people. Elevation of blood pressure at the aortic valve would predictably increase $+G_z$ tolerance.

Human Physiological Response to G

Positive Vertical Acceleration ($+G_z$)

The brain is very sensitive to cellular hypoxia, which produces rapid loss of brain function. Because oxygen is transported to the brain through the cardiovascular/respiratory system, any interruption in arterial blood flow to the brain leads to cerebral hypoxia. However, loss of function does not occur immediately, when blood flow ceases. There is a reserve time of approximately 4 to 6 seconds before loss of brain function begins (5,6).

Physiological control of blood pressure is based (in part) on the closed-loop baroreceptor reflex. Consisting of upper thoracic and carotid body receptors, efferent and afferent nerves, and centrally mediated responses, the baroreceptor reflex controls blood pressure through activation of the autonomic nervous system. When *decreased* transmural pressure is sensed in the upper thorax and carotid bodies, the sympathetic nervous system (pressor response) is activated. When *increased* blood pressure is sensed in the upper body, the parasympathetic nervous system (depressor response) is activated.

The sympathetic nervous system raises blood pressure by increasing its dynamic component. The dynamic component of blood pressure is related to heart rate, stroke volume, and total peripheral resistance. Elevated heart rate and stroke volume both cause blood pressure to increase by raising the volume and pressure of blood injected into the arterial system. Total peripheral resistance is increased when arterial smooth muscle constricts and thereby reduces the circulating arterial blood volume space.

Although very effective in compensating for upper body hypotension, the baroreceptor reflex takes time, on the order of 6 to 9 seconds, with heart-level blood pressure restored in 10 to 15 seconds (7). This compensatory response is therefore slower than the cerebral hypoxia reserve time of 4 to 6 seconds. If sufficient $+G_z$ is experienced, the sympathetic response is inadequate and cerebral hypoxia occurs. A measure of autonomic nervous system response to $+G_z$ is heart rate, which increases directly with increased $+G_z$ level, reaching a maximum within a few seconds of exposure. High-sustained $+G_z$ exposures usually result in a maximum heart rate of approximately 170 beats/minute.

In contrast, the parasympathetic nervous system attempts to lower upper body blood pressure by decreasing heart rate, stroke volume, and total peripheral resistance. This general relaxing of myocardial and vascular tissues occurs quickly, in comparison to the sympathetic nervous system response, and can be fully developed within 2 to 4 seconds (8,9). During $-G_z$, heart rates fall dramatically: reductions of 50 beats/minute have been recorded during exposures of $-3\ G_z$ with some subjects experiencing brief periods of asystole (10).

Adequate cardiac output depends on the supply of blood to the heart through venous return. Although the fluid model might predict that venous return is diminished during increased $+G_z$, early experiments determined that the abdominal contents (as a whole) behave like an enclosed fluid, and that venous return is generally maintained (7).

In addition to the baroreceptor response, sympathetic nervous system dominance is facilitated by the endocrine system. Physiological responses to air combat, aerobatics, centrifuge experiments, or any unusual G-exposure elicit an immediate "fight or flight" response with increased levels of epinephrine, norepinephrine, and serum cortisol (11). The endocrine response is slower than the baroreceptor reflex, but becomes important as G exposures increase in duration.

The respiratory system is also affected by increased $+G_z$. As hydrostatic pressures increase during increased $+G_z$, lung perfusion is redistributed toward the base of the lung, especially at relatively low G levels. During acceleration, the alveolae, owing to the vast differential in specific density between blood and air, expand at the top of the lung while those at the base of the lung, where most blood has moved, become smaller with some collapsing (12). As a result, ventilation/perfusion mismatch and acceleration atelectasis can occur. These responses are further described in Chapter 2.

Increased abdominal pressure during $+G_z$ also prevents full descent of the diaphragm. This impairs vital capacity because of a reduced inspiratory capacity (12). Lung compliance decreases and results in an increased resistance to changes in volume. Reduced compliance and increased weight of the chest wall structures increase the work of respiration in proportion to increased $+G_z$. A total increase of 55% in the work of breathing occurs at $+3\ G_z$. Further details are provided in Chapter 2.

At one time, aerospace physiologists were concerned that human exposures to greater than $+9\ G_z$ could lead to lung tissue injury. These fears have been proved unfounded, at least up to $+12\ G_z$ (13). Former concerns about poor blood oxygenation also proved unfounded, possibly because the major physiologic demands during exposure to G are anaerobic, with physiologic limitations caused by fatigue.

Symptoms and Signs of Uncompensated $+G_z$ Stress

Visual

As $+G_z$ increases, the first symptoms experienced usually consist of visual changes. The interior of the eye is enclosed and normally has an internal pressure of 10 to 21 mm Hg. The retinal artery pierces the posterior globe and enters the central retina with the optic nerve. For retinal blood perfusion to occur, arterial pressure must be greater than the internal eye pressure. If it is not, retinal ischemia occurs, first at vessels farthest from the optic disc and then with progression toward the central retina.

A pilot in flight who is exposed to increasing $+G_z$ can experience dimming of vision, starting at the visual periphery. This is termed *tunnel vision* and is familiar to most pilots who have been trained to expect it. In the presence of continued (and increased) $+G_z$, visual symptoms can progress inward from the periphery to include the central vision, a symptom known as *gray-out*. Not all air crew experience loss of peripheral vision before central vision. If $+G_z$ is reduced, restoration of vision occurs quickly.

With continued or increased $+G_z$, visual symptoms can progress from gray-out to complete loss of vision, or "blackout" (not to be confused with loss of consciousness). Brain and auditory functions remain undisturbed if there is no further decrease in brain-level blood pressure. Recovery from blackout occurs quickly on restoration of blood pressure. The presence of conscious function in the absence of vision can furnish pilots with a valuable warning that loss of consciousness is imminent unless appropriate steps are taken. Because of the repeatability of these symptoms, research studies often rely on subject reports of visual impairment as a measure of tolerance to $+G_z$.

Almost Loss of Consciousness

With increasing $+G_z$, symptoms of early cognitive impairment can develop. This syndrome, termed *almost loss of consciousness* (A-LOC), consists of a transient incapacitation without complete loss of consciousness that often occurs during and after relatively short-duration, rapid-onset $+G_z$ pulses. A-LOC is characterized by a blank facial expression, twitching, hearing loss, transient paralysis, amnesia, poor word formation, and disorientation (14). The most prevalent symptom is reported to be a disconnection between cognition and the ability to act. The duration of incapacitation is much shorter than with G-induced loss of consciousness (G-LOC), reflecting a more transient degree of brain cell ischemia.

G-Induced Loss of Consciousness

If cerebral hypotension progresses beyond the symptoms of visual impairment and A-LOC, G-LOC can occur. G-LOC has been defined as a "state of altered perception wherein (one's) awareness of reality is absent as a result of sudden, critical reduction of cerebral blood circulation caused by increased G force." (15) Centrifuge subjects who experience G-LOC frequently appear to stare blankly before relaxing voluntary muscular control and exhibiting signs of loss of consciousness. Myoclonal jerking is often seen (approximately 70%), semipurposeful grasping and apparent efforts at reorientation are made, and amnesia is sometimes present with a complete unawareness that the event occurred. Following recovery from G-LOC, some subjects (and pilots in flight) have reported "dreamlets" that are similar to sleep dreams, except that they are of very short duration.

G-LOC incapacitation (after reduction of $+G_z$) has been divided into two periods: absolute incapacitation (or unconsciousness) and relative incapacitation. According to centrifuge studies, the average absolute incapacitation period lasts 12 seconds (range of 2 to 38 seconds). This is followed by a period of relative incapacitation consisting of confusion/disorientation that lasts an average of 15 seconds (range of 2 to 97 seconds). A pilot is unable to maintain aircraft control during either of these periods, the sum of which is the total incapacitation period, averaging 28 seconds (range of 9 to 110 seconds). There is apparently no permanent residual pathological effect from an uncomplicated G-LOC.

If rates of onset of $+G_z$ are high, G-LOC can occur before other symptoms, including visual manifestations. Under these conditions, G-LOC can be rapid and lethal because it develops without warning. An example of this was documented several years ago through recovered telemetry data from a CF-18 Hornet jet aircraft. During an exercise combat engagement involving another aircraft, the pilot rapidly loaded the aircraft to +6.4 G_z, then lost control within 4 seconds. The aircraft entered a near-vertical dive and crashed. The data indicated that 18 seconds after the loss of control an attempted recovery was made. The data demonstrated a total period of incapacitation of 18 seconds. The pilot was then able to recognize his situation and attempt recovery—unfortunately too late. Figure 4-9 is a plot of the recorded data.

In practice, it is often difficult to distinguish between A-LOC and G-LOC events. The symptoms and timing overlap, and form more of a continuum than two distinct syndromes. However, both historical and current literature assumes or portrays a clear difference.

Human Tolerance to Sustained $+G_z$

Human tolerance to $+G_z$ has been studied on ground-based centrifuges using human volunteers. Objective measures of tolerance in the past have included ear pulse opacity, direct and indirect measures of blood pressure, and loss of consciousness. A less objective, but more widely used measure, consists of subject reports of visual changes. Unfortunately, reporting is variable and may be influenced by psychological or social pressures, anatomy, and slowed mental processing.

Human tolerance to $+G_z$ is influenced by many variables, including anthropometry (heart-to-brain distance), muscle straining, anti-G suit inflation, and rate of $+G_z$ onset. To control against some of these factors, standardized

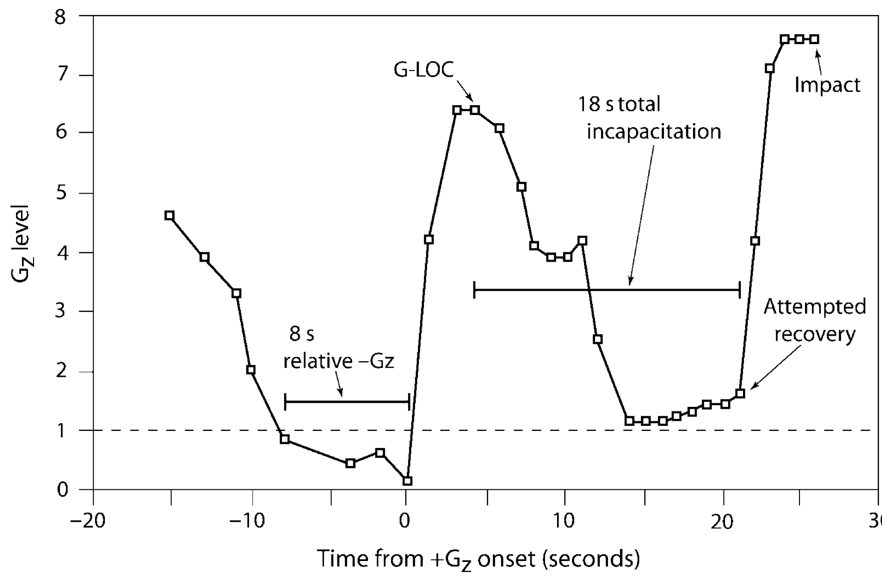


FIGURE 4-9 CF-18 Hornet crash data. These data were recorded during the fatal crash of a CF-18 Hornet. G_z is depicted along the vertical axis whereas time (in seconds) is depicted on the horizontal axis. The plot demonstrates approximately 8 seconds of relative $-G_z$, followed by rapid onset to $+6.4\ G_z$ and G-LOC and loss of control. The next control input was made approximately 18 seconds later with a rapid onset increase to $+7.4\ G_z$, too late to avoid the crash.

approaches have been developed. One is to determine the tolerance of relaxed subjects. This allows for $+G_z$ tolerance to be reported without the confounding influences of muscle strain or anti-G suit inflation, and offers a means of determining passive psychophysiological compensatory responses. Slower G-onset levels allow for cardiovascular compensation to influence the measure. Faster G-onset levels measure tolerance before a full cardiovascular response occurs.

In general, two separate types of subject tests are used, as defined by G-onset rate: (i) rapid-onset rate (ROR) tests and (ii) gradual-onset rate (GOR) tests. ROR is defined as a rate greater than 0.33 G/s, often as high as 6 G/s. GOR is defined as slower than 0.25 G/s. Measurements of relaxed ROR $+G_z$ tolerance are approximately 1 G lower than GOR tolerances. The results of a study involving 1,000 relaxed male subjects reported tolerances presented in Table 4-2A (16). The results of World War II era centrifuge studies, based on subjective reports with onset rates of 2 G/s, are also presented in Table 4-2B (17).

Researchers have studied other potential influences on human tolerance to $+G_z$. Studies assessing female relaxed tolerance to $+G_z$ concluded that they are equivalent to males, with reported ROR tolerances of 4.2 ± 0.5 G and GOR tolerances of 5.2 ± 0.6 G (18). Female time-to-fatigue during simulated air combat maneuvers is not significantly different from that for males (19,20). Menstruation in women on oral contraception has no effect on $+G_z$ tolerance (19). Motion sickness lowers $+G_z$ tolerance (21).

Relative Negative Vertical Acceleration and Negative Acceleration ($-G_z$)

In response to increased relative $-G_z$, heart rate is reduced and generalized vasodilatation occurs, a response that is relatively rapid. This response is dose related in the sense that increased relative $-G_z$, moving toward zero-G and then $-G_z$, results in increasing blood pressure in the upper body and a more vigorous parasympathetic response (10).

During $-G_z$, intracerebral blood pressure increases. Congestion of the face and a subjective sensation of eye bulging occurs; this can become intense with increasing $-G_z$. There is upward movement of the abdominal contents and

TABLE 4-2A

G-level Tolerances of 1,000 Relaxed Subjects Not Wearing Anti-G suits at 1 G/s Onset Rate

Criteria	*Mean G*	*± SD*	*G Range*
PLL	4.1	0.7	2.2–7.1
Blackout	4.8	0.8	2.7–7.8
Unconsciousness	5.4	0.9	3.0–8.4

PLL, peripheral light loss.
(*Source*: Cochran LB, Gard PW, Norsworthy ME. *Variations in human G tolerance to positive acceleration*. USN SAM/NASA/NM 001–059.020.10. Pensacola, 1954.)

TABLE 4-2B

G-level Tolerances of 300 Relaxed Subjects Not Wearing Anti-G Suits at 2 G/s Onset Rate

Criteria	*Mean G*	*±1 SD*
PLL	3.5	0.6
Blackout	4.0	0.6
Unconsciousness	4.5	0.6

PLL, peripheral light loss.
Source: (Code CF, Wood EH, Lambert EH, et al. Interim progress reports and concluding summary of 1942–46 acceleration physiology studies. In: Wood EH, ed. *Evolution of anti-G suits and their limitations, and alternative methods for avoidance of G-induced loss of consciousness.* Rochester: Mayo Foundation Special Purpose Processor Development Group, 1990:409–430.)

the work of breathing is increased. Inverted flight (-1 G_z) can be unpleasant, but tolerable. Between -2 and -3 G_z, there is severe facial congestion and occasional reddening of vision. Most subjects can tolerate -3 G_z for 5 seconds, although some can reach -5 G_z without injury (10,22). The feeling of facial congestion becomes intense at -3 to -4.5 G_z. The restraints, which are supporting the entire mass of the body, cause additional painful sensations. Competitive aerobatic pilots describe sustaining up to -9 G_z for very brief durations.

Some of the adverse effects of $-G_z$ derive from increased arterial blood pressure in the head, especially where it is unopposed. Within the skull, where increased arterial pressures are balanced by increased pressures in the surrounding cerebrospinal fluid, adverse effects are generally not seen (23). Where increased pressures are unopposed, injury can occur. Facial petechiae have been described by competitive airshow pilots. Nose bleeds and subconjunctival hemorrhage have been reported due to high $-G_z$.

There are no generally accepted countermeasures to $-G_z$, although some aerobatic pilots report that they relax while exposed to $-G_z$ so as not to further increase thoracic pressure.

The Push–Pull Effect

Straight and level flying occurs at $+1$ G_z. A pilot experiencing relative $-G_z$ or $-G_z$ will be in a state of enhanced parasympathetic tone after several seconds of exposure. As a result, the pilot will experience bradycardia, diminished cardiac contractility, and vasodilatation.

If the pilot then flies a maneuver involving greater than $+1$ G_z, the upper body blood volume shifts footward into the increased intravascular space caused by vasodilatation. The fall in head-level blood pressure can be profound (Figure 4-10). Recall that the heart was initially in a state of bradycardia and low contractility. In this condition, a full compensatory response can take at least 8 to 10 seconds, with the recovery period dependent on both magnitude of $-G_z$ and duration at $-G_z$ (24–26). Given that the period of hypoxia latency for brain cells is only 4 to 6 seconds, the potential for $+G_z$ related symptoms is clearly enhanced at lower than expected $+G_z$ tolerance levels. Figure 4-10 demonstrates the blood pressure responses of a subject exposed first to $+2.25$ G_z following $+1$ G_z, then $+2.25$ G_z following -1 G_z.

The term *push–pull effect* (which describes the control stick input necessary to cause it) was coined to describe this phenomenon (9). It has been subsequently demonstrated in many studies involving humans and animals, and was demonstrated in humans during in-flight experiments (27).

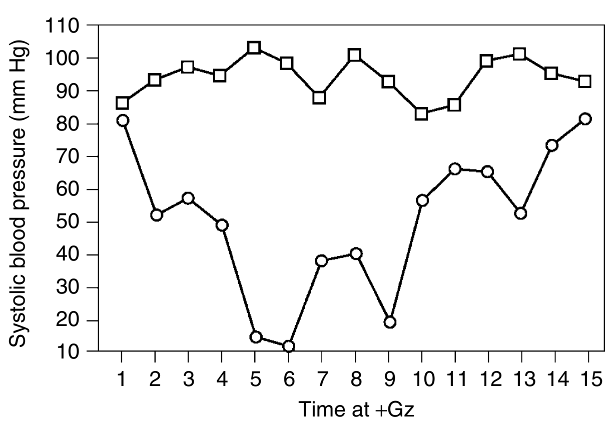


FIGURE 4-10 These blood pressure data were recorded during a centrifuge experiment with a rate of onset of 1 G/s. The upper plot shows the subject's systolic blood pressure response to $+2.25$ G_z following exposure to $+1$ G_z. In the lower plots, the same subject's response to $+2.25$ G_z is shown following pre-exposure to -1 G_z. Note the profound fall in blood pressure in the lower plot. The subject reported symptoms of grey-out, although G-LOC did not occur.

Transverse Acceleration (G_x)

When acceleration acts transversely, the vertical component of the hydrostatic fluid column is very short, and the location of the brain relative to the vertical column does not make the brain vulnerable to changing hydrostatic blood pressures. Predictably, centrifuge studies have demonstrated that the cardiovascular effects of $+G_x$ are less than with $+G_z$. Negative G_x cardiovascular effects are generally similar to those of $+G_x$. If the head is elevated during $+G_x$ exposures, heart rate increases, indicating some baroreceptor effect.

There is, however, considerable difference between $+G_x$ and $-G_x$ with regard to lung volumes and ventilation. At $+6$ G_x, for example, vital capacity is reduced 55% to 80% over 1 G values, whereas at -6 G_x, there is only a minor decrease in vital capacity (28). Lung perfusion during $+G_x$, much like $+G_z$, is unevenly distributed within the lung: there is increased blood volume (shunting from right to left) near the back of the lung and no perfusion at the front. One minute at -6 G_x results in no reduction in arterial saturation.

Breathing effort increases during increased $+G_x$ and, with reduced functional lung volumes, a higher breathing frequency occurs with an increase in functional dead space. The increased breathing effort during $+G_x$ is caused by a major increase in the elastic component of the lung, with the total breathing effort doubled at $+4$ G_x over 1 G (29). Oxygen consumption increases. Acceleration atelectasis occurs at $+5.6$ to -6.4 G_x in subjects breathing 100% oxygen and not wearing an anti-G suit. Because lung volumes are not restricted during $-G_x$, acceleration atelectasis is not a problem. At higher $+G_x$ levels, the inability of the subject to expand the chest wall upward (breathe) against the $+G_x$ force limits human tolerance to approximately $+15$ G_x (30).

Despite the increased ability of humans to tolerate $+G_x$, this position has not been used as an anti-G system in high-performance aircraft. However, National Aeronautics and Space Administration (NASA) and Soviet spacecraft have employed the $+G_x$ configuration to protect astronauts from high-G exposures during launch. This configuration is also used during entry of manned capsules, although the returning space shuttle exposes astronauts to predominantly $+G_z$ (Table 4-5) (31).

Lateral Acceleration (G_y)

The brain is also not directly threatened during G_y because of the relatively short vertical hydrostatic column that exists in this orientation. G_y is rarely encountered in current aircraft. It may become an important concern in future aircraft capable of lateral thrust-vectored propulsion (TVP). The most important physiological problem involving lateral acceleration up to ± 6 G_y is dyspnea as a result of ventilation/perfusion inequalities. Radiologic images demonstrate marked displacements of the heart and compression of lung toward the acting forces (32). Research involving G_y has demonstrated reductions in blood oxygen saturation levels starting 10 to 15 seconds after the onset of G_y. This trend is worse for $+G_y$ compared to $-G_y$, and neck discomfort is problematic beyond 3 G_y (33).

Multiaxis Acceleration

Multiaxis accelerations can occur during flight maneuvers involving thrust-vectored aircraft such as the United States Air Force (USAF) F/A-22 or the Russian Su-37, and can either enhance or reduce relaxed tolerance to the $+G_z$ component of acceleration. Simultaneous G_y and G_z enhance $+G_z$ tolerance, whereas simultaneous G_x and G_z can reduce $+G_z$ tolerance. These differences are small and unlikely to affect operations (34).

Morbidity and Mortality

The overall incidence of in-flight G-LOC among military aircrew during their careers is between 8% and 25% (35–37), levels that have remained steady over the last 20 years. Reported G-LOC incident rates for trainer, attack, and fighter aircraft average 25.2 events per million sorties (PMS). However these rates range from 1.4 G-LOCs PMS for two-crewmember fighters to 112.4 PMS for basic trainers (37). Most such incidents occur during training flights, and usually affected aircrew who were not in control of the aircraft when their G-LOC occurred (35), a factor that prevented crashes. Although centrifuge training programs have been associated with decreased reports of in-flight G-LOC, reduced incidence of in-flight G-LOC was not noted among USAF pilots in the 1990s (38). Inexperienced pilots report more incidents of G-LOC (38).

Mission type rather than aircraft type influences the G-LOC incidence. The G-LOC rate in the USAF by aircraft category is reported in Table 4-3 (37). For a variety of reasons, including amnesia of the event, self-reports of in-flight G-LOC are certainly underestimated.

The push–pull effect has been implicated as an important cause of G-LOC in flight. A recent Royal Air Force (RAF) study reported that approximately 31% of in-flight G-LOC was due to push–pull effect, similar to the 29% reported in a separate study conducted by the USAF (35,39). Push–pull effect–like maneuvers were previously reported as a problem in competitive aerobatic flying (40). Although the push–pull effect is most applicable to trainer, fighter, and civilian aerobatic aircraft, the flight envelopes of modern helicopters give rise to the possibility that A-LOC can occur during aggressive flight operations (41).

TABLE 4-3

United States Air Force (USAF) G-induced Loss of Consciousness (G-LOC) Event Rates by Aircraft Category (1982–2002)

Aircraft	*Sorties*	*Events (Rate[a])*	*Expected Events*
Single crewmember fighters	7,640,702	83 (10.9)	193
Two-crewmember fighters	2,919,320	4 (1.4)	74
Attack	2,784,219	5 (1.8)	70
Basic trainers	4,091,059	460 (112.4)	103
Advanced trainers	4,631,538	6 (1.3)	117
Total	22,066,838	558 (25.2)	

[a] Per million sorties (PMS).

(*Source*: Lyons TJ, Craft NO, Copley GB, et al. Analysis of mission and aircraft factors in G-induced loss of consciousness in the USAF: 1982-2002. *Aviat Space Environ Med* 2004;75: 479–482.)

The identification of G-LOC as a causal factor in crashes is complicated by the lack of data and survivor information that accompany such events. Crashes due to suspected G-LOC are usually fatal and involve single-pilot aircraft. Overall, in the USAF, 20 fatalities have been caused by G-LOC in recent years (37). A Canadian CF-18 was lost due to G-LOC during an air combat training exercise in 1995 and push–pull effect was found to be causal (Figure 4-9). The loss of an F-20A Prototype Tigershark in Canada in 1987 was also attributed to G-LOC by the investigating board. A case of G-LOC has been reported in general aviation (42).

Protection Against the Effects of $+G_z$

Protection against the effects of $+G_z$ can be approached through several means, including: (i) decreasing the vertical heart-to-brain distance, (ii) limiting duration to less than 4 to 6 seconds, (iii) increasing blood pressure at the aortic valve, and (iv) avoiding the push–pull effect.

Decrease Heart-to-Brain Distance

The most effective means of enhancing $+G_z$ tolerance, as well as protecting the pilot, is to reduce the vertical height of the heart-to-brain distance. This reduction can be made possible by having the subject tilt either forward (prone) or backward (supine) relative to the $+G_z$ vector. The approach has been used in the design of modern fighters including the F-16. The heart-to-brain distance can also be reduced by the presence of an anti-G suit (by elevating the diaphragm).

Limit Duration

Civilian competitive aerobatics pilots, who do not use anti-G suits, report experiencing up to $+12$ G_z and levels of $-G_z$ approaching -9 G_z. Because many such pilots perform sustained inverted flying maneuvers, susceptibility to the push–pull effect is an acknowledged threat. However, due to aircraft thrust limitations, most competitive aerobatic aircraft are not capable of prolonged sustained G_z, and the pilots are able to tolerate these high levels because exposure times are less than 4 to 6 seconds.

Increase Aortic Valve Blood Pressure

Any measure that safely increases aortic valve blood pressure, as a means of countering the increased hydrostatic component of blood pressure during increased $+G_z$, will enhance human tolerance. The most effective way of accomplishing this goal is by utilization of the anti-G strain maneuver (AGSM), first developed during World War II.

Anti-G Strain Maneuver

The AGSM consists of forced exhalation against a closed glottis (L-l maneuver) or partially closed glottis (M-1 maneuver) while tensing leg, arm, and abdominal muscles. The AGSM effort is interrupted at 3- to 4-second intervals with a rapid (<1 second) expiration/inspiration, which allows adequate venous return during the period of low intrathoracic pressure. Although head-level blood pressure falls to nearly zero in conjunction with lowered thoracic pressure, the time is so brief that the brain maintains unaltered function.

Tensing increases intrathoracic pressure, which is directly transferred to arterial pressure at heart level. With increased $+G_z$, and despite cardiovascular compensation, cardiac output decreases because of the reduced stroke volume as a consequence of the fall in venous return (43). Muscular tensing of the legs is used to increase vascular resistance to assist venous return.

The AGSM technique is learned. An effective teaching platform is formal AGSM training on a human-use centrifuge. Training that includes simulated air combat has proved effective in enhancing tolerance. A well-trained and current pilot can raise $+G_z$ tolerance by up to 3 G (44). One recent training program included push–pull effect maneuvers (45).

The AGSM is fatiguing. Physiological support for the AGSM is primarily anaerobic with muscular strength as a principal factor in its intensity. Both anaerobic capacity and muscular strength can be increased with training. Strength training has been shown to increase $+G_z$-duration tolerance. Suddenly ceasing to perform an AGSM, while still at elevated $+G_z$, predictably leads to G-LOC.

Anti-G Suits

The anti-G suit (also termed *G-suit*) is designed to provide transient hypertension at the aortic valve to overcome hydrostatic pressure. Two general approaches to the design of anti-G suits have been taken: hydrostatic and pneumatic. Hydrostatic anti-G suits use fluid within the suit to provide counterpressure to the body simultaneously with $+G_z$ stress. These suits are self-contained, require no aircraft support or attachments, and provide an instant response. The first operationally deployed anti-G suit used this principle (7).

FIGURE 4-11 On the left is a conventional anti-G suit used during World War II. On the right is a modern anti-G suit used in the CF-18 Hornet. Note the small change in the basic design over 50 years.

It was soon abandoned in favor of the lighter and more comfortable pneumatic designs, but the modern Libelle suit has signaled a return to this concept. Figure 4-11 consists of a photograph of a conventional anti-G suit that was used operationally in World War II and a photograph of a modern conventional anti-G suit.

The pneumatic anti-G suit generally consists of pressure bladders inside fabric coveralls that cover the abdomen, thighs, and calves. Air pressure is supplied to the bladders through control valves at rates that depend on the level of $+G_z$. The suits are designed to be tightly fitted with zipper fasteners and air hose connectors that attach to the aircraft. Successfully developed in World War II in several versions, the design evolved after the war to include less body surface coverage for increased comfort. With the advent of aircraft capable of higher and more sustained $+G_z$, designs reverted to the enhanced body coverage of the earlier era.

Conventional anti-G suits increase aortic valve blood pressure by (i) increasing total peripheral resistance through mechanical compression of the abdomen and legs, (ii) raising the position of the heart to decrease the vertical distance to the brain, and (iii) increasing venous return. Optimum response time for suit inflation is within 1 second of reaching the maximum $+G_z$ level. The effectiveness of an anti-G suit depends on the amount of pressure applied (and tolerated) to the abdomen and trunk, the area of application, and the volume of the bladders. In general, highest protection is afforded at the highest tolerable pressure, and depends on the subject and suit fit.

A conventional anti-G suit increases relaxed ROR and GOR tolerances by approximately 1 to 1.5 G. Protection is dependent on a properly tight fit with all "comfort zippers" worn and closed. The USAF Advanced Tactical Anti-G Suit (ATAGS), a suit that covers a greater portion of the legs and abdomen, increases G-tolerance by an additional 0.5 to 1.0 G. The protective qualities of the anti-G suit are generally considered additive to the protection afforded by the AGSM.

Therefore, a pilot who has a resting tolerance of $+5\ G_z$ would be expected to tolerate up to $+9$ to $+10\ G_z$ with a properly functioning anti-G suit and a well-performed AGSM.

To prevent fatigue during air combat maneuvering, assisted positive pressure breathing for G (PBG) was developed. The concept works by increasing mask pressure during $+G_z$ with the result that pilots must exhale forcefully. Inspiration is also assisted and augmented. The increased inspiratory pressure, and forced exhalation, increases intrathoracic pressure and thereby aortic valve blood pressure.

An example of this technology is the USAF version of PBG, the COMBAT EDGE. COMBAT EDGE uses a chest-counterpressure garment (jerkin) that is worn and inflated at the same pressure as the breathing mask delivering the increased intrapulmonary pressure. This jerkin counteracts high levels of positive pressure breathing by supporting the chest. Research has explored whether the counter pressure jerkin is necessary for PBG under all circumstances. A counter pressure jerkin is necessary when positive pressure is utilized for altitude protection, but the increased weight of the chest when a pilot is exposed to G may provide sufficient counter pressure for PBG in other conditions.

PBG reduces the fatigue that develops during high-G maneuvers, because the requirement to perform an AGSM is reduced by approximately 50%. The PBG/ATAGS combination and reclined seatback offers high-G protection that will allow many pilots to tolerate $+9\ G_z$ sustained with minimal or no AGSM (13). This type of design is currently in use in the F-22, Typhoon, Finnish F-18, and Norwegian F-16. Significant benefits have been reported by pilots using these suits. Studies of the full-coverage PBG concept report that trained subjects can tolerate five simulated flight sorties over 4 hours with up to 80 peaks to $+9\ G_z$ and 80 peaks to $+8\ G_z$ (46).

Avoiding the Push–Pull Effect

Apart from efforts to inform pilots of the hazards of the push–pull effect, no countermeasures against the problem have yet been developed.

Potential Harmful Effects of Sustained G

In general, exposure to G_z within the acceleration capabilities of current aircraft does not lead to permanent injury. Most reported injuries are minor and consist of neck strains. No permanent sequelae to centrifuge G-LOC, even when repeated, have been reported.

Although animal studies have demonstrated myocardial injury from tolerable levels of increased $+G_z$, these results are not considered applicable to humans. No pathologic changes were detected during the autopsy of a highly exposed centrifuge subject (47). A cross-sectional study found no differences in right and left ventricular dimensions and wall thickness, aortic and left atrial dimensions, and tricuspid and mitral inflow velocities of pilots compared to nonpilots (48).

Cardiac dysrhythmias, usually benign, have been documented during centrifuge studies. These dysrhythmias are generally considered to be due to changes in the electrical mechanism of the heart. Seldom are there symptoms of compromise to $+G_z$ tolerance. The incidence of in-flight dysrhythmias may be lower than the reported incidence derived from centrifuge experiments. No clinically significant in-flight dysrhythmias have been recorded.

Acceleration (or aero-) atelectasis syndrome is associated with increased $+G_z$ exposure in pilots who breathe oxygen-enriched gas mixtures (>70% oxygen) and wear an inflated anti-G suit. Symptoms include retrosternal chest pain or discomfort, dyspnea, and episodes of paroxysmal coughing. This condition occurs because the downward movement of the lung is opposed by the upward shift of the diaphragm caused by inflation of the abdominal bladder of the anti-G suit, thereby compressing lower lung tissue and closing the distal alveolae. Oxygen in these isolated alveolae is rapidly absorbed into the blood, resulting in their collapse. Not surprisingly, breathing oxygen can contribute to acceleration atelectasis (49). There is a high degree of individual susceptibility to acceleration atelectasis, which may be increased by tobacco smoking.

Movement of viscera due to G_z is known to occur, but reports of associated injuries are rare. The heart is known to move within the thorax and relative to the diaphragm under G_z loading. There has been a single report of renal artery dissection as a result of visceral movement during $\pm G_z$ (50), and one occurrence of acute inguinal hernia thought to be associated with the AGSM (51).

Musculoskeletal symptoms are probably the most common complaints associated with $+G_z$. Neck pain is often associated with extremely rapid-onset $+G_z$ during aerial combat or aerobatics, usually when the neck is near maximum rotation. The risk of neck injury may be associated with a reclined seat and the presence of a helmet. Although radiologic studies conducted at up to $+6\ G_z$ have shown no measurable narrowing of intervertebral spaces (17), some consider degenerative conditions likely as a result of repeated overloading of vertebrae. A recent study using magnetic resonance imaging (MRI) did not find a high prevalence of cervical degeneration changes among a small number of fighter pilots (52).

Pain is sometimes reported in dependent areas subject to venous congestion, especially with use of full coverage anti-G suits. These complaints include reports of arm pain that has been treated successfully with inflatable arm cuffs. Also found in dependent and unsupported areas of the body are small, pinpoint, cutaneous petechiae (previously discussed), often called *G-measles* or *Geasles*. They resolve in several days without sequelae. Occasional problems with larger vessels have been reported, including superficial lower extremity phlebitis and hematomas, and there is an anecdotal belief among pilots of an increased incidence of hemorrhoids.

The Limitations of Current Knowledge

In the past, human tolerance to increased $+G_z$ was associated with magnitude, duration, rate of onset, use of countermeasures, and individual susceptibility. Pre-exposure G_z-history (e.g., the push–pull effect) was not considered a risk factor to reduced $+G_z$ tolerance.

Human centrifuges usually consist of a capsule (or gondola) mounted at the extremity of a rotating arm. G varies with the distance from the center of rotation and with the velocity of the capsule according to Equation 4. The capsule is usually attached to the end of the rotating arm in a manner that allows it to roll passively into alignment with the resultant G-vector, which is the vector addition of rotational-G and gravity. An upright-seated occupant inside the capsule then experiences $+G_z$.

All human centrifuges create accelerations greater than $+1$ G_z. To create other directions of G, the capsule, or the occupant and seat, are mechanically rotated out of alignment with the resultant G-vector. For example, $-G_z$ can be produced if the centrifuge subject is inverted within the capsule so that the subject is "head-out" from the center of rotation. G_x and G_y are achieved when the subject is presented transverse to the resultant G-vector. In the past, most centrifuges did not have this capability or were unable to change acceleration directions during rotation. Less than half of present-day centrifuges have this capability.

Another limitation of centrifuges is the need to mitigate the potentially disorienting cross-coupled effects on the inner ear of the centrifuge subject. This is accomplished by starting slowly and gradually increasing the rotational velocity of the centrifuge until a "baseline" condition is achieved. The baseline, which typically varies from $+1.2$ to $+1.8$ G_z, represents the starting level.

These situations contrast with actual flight conditions. Figure 4-12 depicts the accelerations recorded during two F/A-18 sorties (53). Note that 5% to 6% of flight time during these sorties was conducted at less than $+1$ G_z, with even more time spent at less than $+1.2$ to $+1.8$ G_z. Figure 4-9 demonstrated the acceleration profile of a fatal CF-18 crash. Immediately preceding the loss of control, the pilot experienced relative $-G_z$, which led to G-LOC.

In a separate study of 240 USAF air combat engagements, it was found that up to 67% of engagements included maneuvers that could provide the push–pull effect (54). Table 4-4 illustrates the incidents.

The great majority of the thousands of studies involving acceleration research during and after World War II occurred at levels greater than $+1$ G_z. The variable of preceding G_z-history was not considered. The experimental conditions, for the most part, were imposed by the capabilities of the centrifuges and the lack of appreciation of the potential role of preceding G_z. The variable of preceding occupant G_z-history has therefore not been widely considered in the design of countermeasures, including anti-G suits.

The Future

Current and future crewed fighter aircraft will employ TVP, which is the redirection of engine thrust in flight (55). TVP enables "high-agility" maneuvering, which is the capability of an aircraft to maintain controlled flight at speeds below that of the airframe stall speed. Current aircraft employing aspects of this technology include the Lockheed Martin F-22, versions of the F-15, F-16, F-18, the Mikoyan-Gurevich MiG 35 MFI, Sukhoi Su-37, and the Su-47.

The tactical advantages of high-agility flight include improved capabilities in "point-first" missile attack, ground

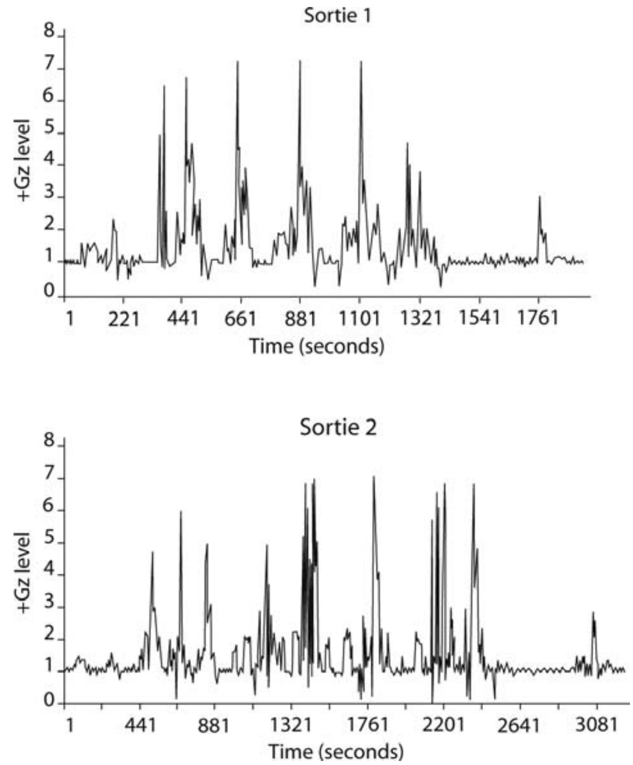


FIGURE 4-12 Two F-18 flight profiles recorded during air combat maneuvering.

TABLE 4-4

Percentage of Engagements with Push–Pull Effect Maneuvers by Type of Sortie, Pilot Status, and Aircraft Type

Sortie Type	*Pilot Status*	*F-16*	*F-15*	*Aircraft Combined (%)*
BFM	Student	11/30(37%)	7/43(16%)	25
BFM	Instructor	3/28(11%)	5/35(14%)	13
ACM	Student	18/42(43%)	16/24(67%)	51
ACM	Instructor	12/32(38%)	5/8(63%)	43
Aircraft totals		44/132(33%)	33/110(30%)	132

BFM, basic fighter maneuvers; ACM, air combat maneuvers.

(*Source*: Michaud V, Lyons T, Hansen C. Frequency of the "push-pull effect" in U.S. Air Force fighter operations. *Aviat Space Environ Med* 1998;69:1083–1086.)

attack, reconnaissance, missile avoidance, high-altitude operations, short take-off and landing, automaneuvering, stealth, and safety. Flight maneuvers, such as the Herbst and Cobra maneuvers, have evolved. It is expected that $+G_z$ exposure magnitudes in the future will be of lower magnitude, but increased frequency. Negative-G_z exposures will be more frequent. G_y exposures, now rarely experienced, will become more common and G_x stress will increase in magnitude with improvements in propulsion systems (55).

A knowledge gap exists. Current $+G_z$ countermeasures, including anti-G suit technology, provide inadequate protection against the stresses of high-agility flight. Pneumatic or hydraulic anti-G suit technology that responds quickly to the array of internal hydrostatic pressure challenges will be needed. Hopefully, individualized closed-loop algorithm-based systems, that incorporate the variable of preceding G_z-history, will be developed.

Thirteen years after the identification of push–pull effect, and 10 years after it was first identified as causal to upward of 30% of G-LOC incidents, an effective countermeasure has yet to be devised.

Space Operations

Space vehicle launch and entry involve significant accelerations. Table 4-5 summarizes some of the accelerations experienced during manned spaceflight (31).

In order to tolerate these accelerations, astronauts are orientated to experience $+G_x$ both before and during launch (Figure 4-13). Space capsule seating has involved rigid contoured seats, while seating within the Space Transportation System (STS) space shuttle crew module consists of up to seven conventionally aligned seats, five of which are removable during flight. The seats are rigid in construction, fastened to floor structures, and equipped with conventional five-point restraint harnesses. Personal life-support equipment includes full pressure suits with helmets, detachable gloves, boots, and parachutes. The space shuttle does not have ejection seats and emergency escape is through a bailout procedure.

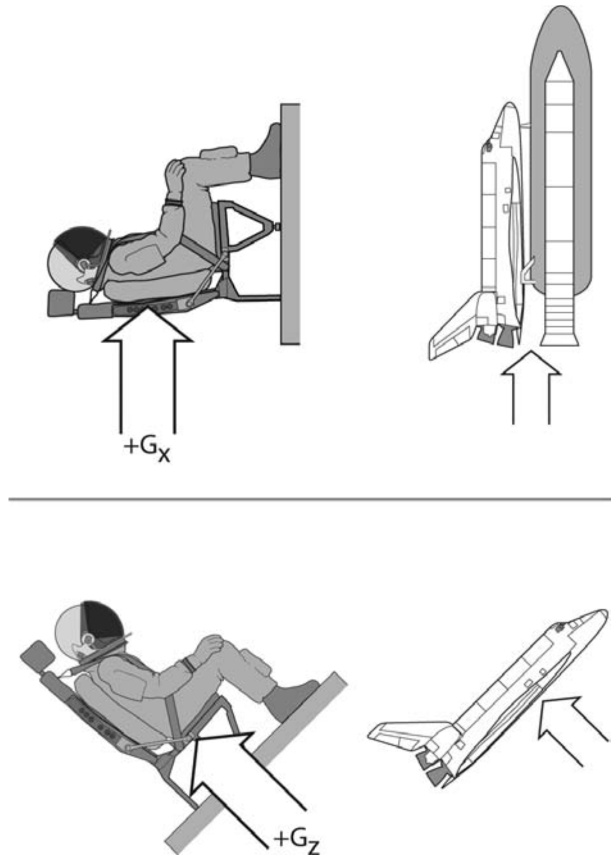


FIGURE 4-13 The top diagram depicts the orientation of astronauts before and during launch of the space shuttle and Soyuz. In this orientation, they experience $+G_x$ during launch. In the lower depiction, the orientation of space shuttle astronauts during entry is shown. While encountering increased atmospheric drag, the crew experiences predominantly $+G_z$ (*Source:* John Martini, BRC).

TABLE 4-5

Spacecraft Launch and Entry Acceleration Profiles

Vehicle	*Launch Profile*	*Reentry Profile (Average Max G)*
Mercury-Atlas	6.0G for 35 s and 6.4G for 54 s in two phases over 6 min with peaks of 8.0G	8.9G (range 7.6–11.1G)
Voskhod		3.0–4.0G
Gemini-Atlas	Peaks of 5.5G and 7.2G	5.7G (range 4.3–7.7G)
Soyuz	3.4–4.0G	3.0–4.0G
Apollo-Saturn	Little >4.0G	5.9G (range 3.3–7.2G) for up to 60 s.
Space Shuttle	3.4G	1.2G for 17 min

Because the space shuttle is vertically aligned to the Earth before launch, seated astronauts experience $+1G_x$ (gravity). As acceleration builds during the climb-out from the Earth, $+G_x$ stress increases to approximately $+3\ G_x$. Positive-G_x is best tolerated because the hydrostatic column is aligned in a manner that does not directly threaten intracerebral function, but the work of breathing is increased (as described previously).

Once orbital insertion has occurred, astronauts begin a freefall and experience no G due to gravity. In aerospace medicine, this is termed *microgravity*. During a suborbital launch into space (Space Ship One), zero-G is experienced for a short period, but the spacecraft soon falls to Earth.

In microgravity, there is no hydrostatic blood pressure component and all blood pressure is due to the dynamic component, which is undiminished at head level. Leg volume decreases and facial soft tissues expand. There are initial increases in the size of the heart, and cardiac output and stroke volume are increased. Cardiopulmonary receptors, which function to control blood volume on Earth, stimulate adaptive mechanisms aimed at reducing blood volume. Plasma volume drops rapidly, probably through movement into the extravascular space (56). Blood volume is decreased, likely as a result of reduced erythropoietin secretion. With the overall reduction of physical activity in space, cardiac muscle mass is reduced (along with other muscles). Cardiac rhythm disturbances have been reported (56).

On return to Earth, manned space capsules enter the atmosphere in an attitude that again results in $+G_x$ stress to the crew. The space shuttle attitude during entry leads to $+G_z$ stress that averages $+1.2\ G_z$ for 17 minutes before touchdown (Table 4-5). The combination of muscle atrophy, reduced cardiac mass, and dehydration in the presence of significant fluid shifts, are preconditions for reduced $+G_z$ tolerance during this phase. As part of entry procedures, shuttle astronauts rehydrate and wear anti-G suits with optional inflation levels. Normal procedures call for strap-in to be complete before entry-interface (first interaction with atmosphere). Since the loss of Challenger in 1986, all shuttle crews have been required to wear an anti-G suit during entry. Those who inflate the suits have better protection against $+G_z$ during entry and landing (57).

$+G_z$ Tolerance Models: A Need for a Revision

The most generally accepted model of $+G_z$ tolerance was proposed by Alice Stoll in 1956 (58). This model was based on original experimental data, and was integrated with the results of similar experiments conducted in other laboratories. A G-tolerance curve that incorporated various acceleration rates was created. Other versions of this curve have been presented in previous editions of this book. The Stoll G-tolerance curve is reproduced in Figure 4-14.

The Stoll curve was based on centrifuge studies and therefore describes the experiences of healthy young males exposed to accelerations greater than $+1\ G_z$. Although it adequately describes the tolerances of subject populations involved in centrifuge research, the use of the Stoll plot (and other similarly derived models) should be viewed with caution when applied to operational conditions.

When pre-exposure G_z-history is considered, predictions based on the Stoll model will overestimate human tolerance. The extreme example involves space flight operations. As discussed previously, space flight leads to physical deconditioning and markedly reduced tolerance to $+G_z$, including the $+1\ G_z$ of gravity. Much shorter durations of zero-G, like those experienced during atmospheric ballistic flights to train astronauts, have led to symptoms of reduced $+G_z$ tolerance during the moderate $+ G_z$ of aircraft recovery. To illustrate the problem, we have added a line to the Stoll plot in Figure 4-14 showing reports of visual light loss from subjects exposed to $+2.25\ G_z$ after the preceding $-G_z$ (24). The line falls below the predicted tolerance predicted in the Stoll curve.

When considering pre-exposure G_z-history, both magnitude and duration of G_z, two separate but associated variables must be considered. Modeling, based in part on the Stoll data, has aimed at predicting the cognitive and blood pressure effects of these two variables on subsequent $+G_z$ tolerance. This modeling demonstrates the inadequacies of Stoll-like predictive models when $+G_z$-history is considered (59).

A revised model is needed, particularly in light of ongoing progress toward space tourism and the likelihood that pilots and passengers of commercial space vehicles will be exposed to stresses of flight that are, as yet, incompletely understood. The variable of pre-exposure G_z-history is now added to the list of risk factors for G-LOC. The Stoll curve, long relied upon, should be viewed as a evolving, dynamic entity that varies with $+G_z$-history.

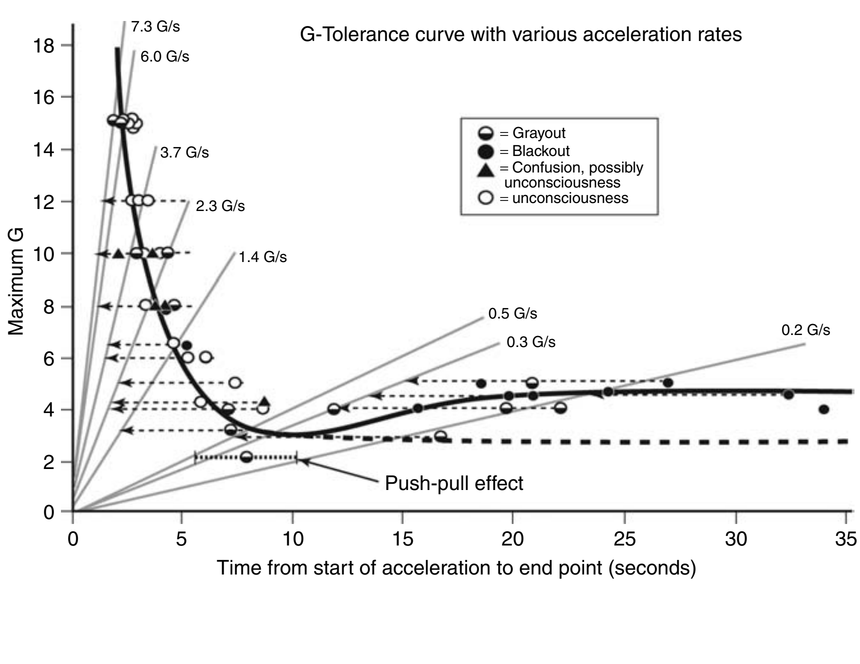


FIGURE 4-14 Stoll $+G_z$ tolerance curve. A line has been added to the plot to show a range of visual symptom reports among subjects pre-exposed to $-1\ G_z$ or $-2\ G_z$ (labeled the push–pull effect).

TRANSIENT ACCELERATION

Transient acceleration is encountered by aircrew both in the course of flight operations and during emergencies. Operational exposures to transient acceleration include aircraft carrier catapult launches, barrier engagements, and capsule recovery impacts. Transient accelerations are also encountered during emergencies that involve ejection, parachute opening, and ground landings. Crashes involve very large and injurious levels of transient acceleration.

Transient and sustained accelerations are often delineated in terms of duration. For example, acceleration events having durations of less than 1 or 2 seconds have been defined as impacts by various authors. However, a fixed-time duration definition is not always applicable over the range of acceleration profiles of interest in aerospace medicine. Depending on how brief an impact duration is, the result on an aircrew member can range from little noticed to catastrophic. The injury outcome may provide the best way of considering the issue: traumatic injury is associated with transient acceleration; challenges to homeostasis are associated with sustained acceleration.

The designs of space vehicles, cockpit escape modules, ejection seats, parachutes, and restraint systems have been based on human tolerance data derived from research using volunteers, cadavers, and animals. This section begins with a brief review of the basic mechanics of transient acceleration, and then describes the current understanding of human tolerance. Emergency crew escape, crew protection, and aircraft crashes are then discussed.

Work and Energy

One convenient way of understanding transient acceleration is through the concept of energy, which can be considered as the ability to do work. Kinetic energy is a form of energy that exists by virtue of motion. Kinetic energy is expressed as:

$$E = 1/2\ mv^2 \qquad [8]$$

where E = kinetic energy.

Kinetic energy is proportional to velocity squared and varies directly with mass. For example, a 6-mm diameter bolt in low-Earth orbit has about the same mass but 10 times the velocity of a military rifle bullet, and hence 100 times its energy.

With energy, work can be accomplished. A hammer strikes a nail and the nail is driven, against friction, a certain distance into a board. Assuming all the energy has gone into moving the nail into the board, the kinetic energy of the hammer was converted to work.

Work is defined as the product of force and distance, or:

$$W = Fx \qquad [9]$$

where W = work and x = distance.

Of interest, the units of work and energy are the same, and, as a practical consequence, they are equivalent. If all of the kinetic energy of an impact event is used in work (an assumption), it is possible to estimate the average acceleration of the event as follows:

$$E = W \text{ or, } 1/2\ mv^2 = Fx \qquad [10]$$

which leads to:

$$a = v^2/2x. \qquad [11]$$

When the acceleration is applied to an occupant who is perfectly fixed to the aircraft (another assumption), the G on the occupant can be expressed as:

$$G = v^2/2gx. \qquad [12]$$

Consider the scenario of an aircraft in flight impacting the terrain. In the moment before impact, the aircraft possesses kinetic energy according to its velocity and mass (Equation 8). After striking the terrain and decelerating through a distance, the aircraft comes to rest and its kinetic energy is zero. This is depicted in Figure 4-15A. If we assume that all the kinetic energy is converted to work (for example, by destroying aircraft structures, or reacting to opposing forces), and we know the distance of the deceleration, we can estimate the *average* G of an occupant fixed to the aircraft by using Equation 12.

Note that in Figure 4-15B, the same example is presented, but the depicted distance of deceleration is much shorter than that of Figure 4-15A. If we again use Equation 12, the calculated average G would then be greater. The crash at Figure 4-15B is clearly the more severe in terms of occupant exposure to G, and the severity relates to the deceleration distance and velocity.

These estimates are based on a constant deceleration, which never occurs in a crash. Crash events are usually measured on a time scale of a few hundred milliseconds. Within this scale, deceleration (and associated crash forces) starts at zero, rise to a peak, and end at zero when the event is over. Therefore, the greatest acceleration, or "peak-G" is often of more interest. An estimate of peak-G can be made by doubling the average estimate from Equation 12. When more information is available, a more robust analysis using nonconstant accelerations can sometimes be generated.

These very important concepts underlie all that will be discussed in this section. For the same velocity and mass, the acceleration experienced by an aircraft, and the G experienced by the occupant, depends (in part) on the distance of deceleration. Protection from injury is usually enhanced when the kinetic energy can be dissipated over a greater distance.

Kinematics and Biomechanics

Kinematics involves the analysis of motion without reference to force. Biomechanics is the description of the effects of mechanics (force, energy, acceleration, momentum) on humans affected by transient acceleration. Descriptions of impact response usually involve the displacement of the subject with respect to the vehicle. One way in which displacement can increase occupant accelerations is by imposing shorter stopping distances for some parts of the body, a phenomenon seen during a crash landing. In such events, the initial velocity of the aircraft is rapidly decreased to zero relative to the terrain.

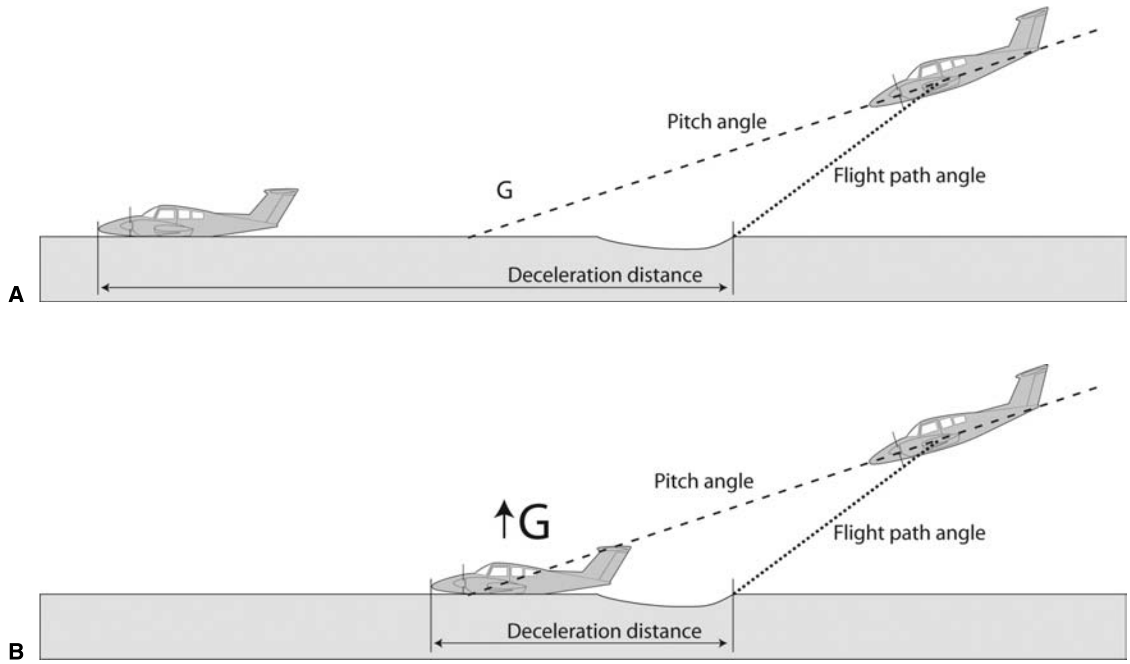


FIGURE 4-15 **A:** Aircraft at rest following crash into terrain. The aircraft has impacted the terrain and translated to a stop. The total distance of deceleration is indicated. A resultant average deceleration is depicted with "G." (*Source:* John Martini, BRC). **B:** This depiction shows the same aircraft, but with a much shorter stopping distance. Because the distance is shorter (and referring to Equation 12), the average "G" is greater. The associated forces and potential for injury would also be greater when compared to **A** (*Source:* John Martini, BRC).

For a human involved in a frontal crash, the head continues forward at the preimpact velocity until influenced by a force that acts to cause an acceleration. In this example, the force is provided by the neck that is ultimately placed in tension as the head continues forward with respect to the rest of the body (Figure 4-3). A velocity difference is therefore built up between the head and the body, because the latter is restrained by the straps of the restraint harness. The head will then have to undergo the same velocity change but in less time than the body because it starts to decelerate later: both the body and the head must finally reach zero velocity. Displacement of a pilot from a normal cockpit position may allow the pilot to strike a portion of the aircraft, such as the instrument panel. This leads to increased head accelerations.

The manner by which an occupant is coupled to contact surfaces influences their response to transient acceleration. For example, helmets act as buffers to increase the distance over which the head changes velocity. Restraint systems allow individuals to remain fixed to the aircraft while it decelerates through a crumpling crush zone. Ejection seat propellant cartridge catapults, and rockets ignited upon entering the wind stream, provide the acceleration necessary to escape from the aircraft.

Even when surfaces and equipment are optimally designed, human tolerance to the energy of transient acceleration has its pathophysiological limit. If designs are in place that can lower the G experienced by an occupant during a crash, protection against trauma can be afforded. Some helicopters have stroking seats that help protect the spine during vertical impacts. The principle of stroking seats is to increase the distance of deceleration and thereby decrease the G experienced. This is illustrated in Figure 4-16.

By increasing the distance of deceleration of the pilot during the crash, forces are reduced and injury potential is lessened.

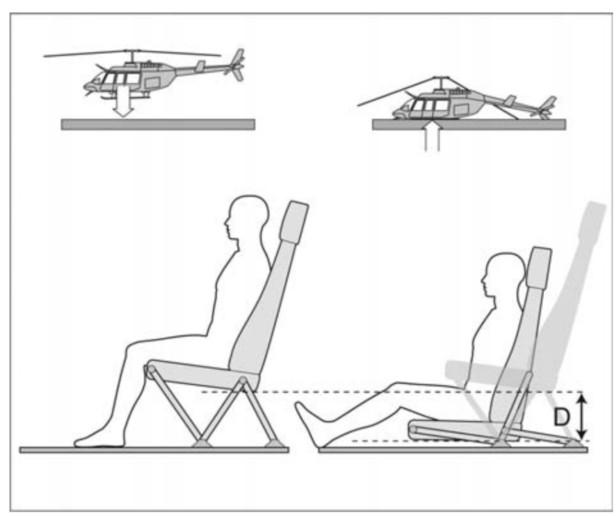


FIGURE 4-16 The principle of stroking seats. A design that allows the seat to stroke downward in a vertical impact increases the distance of deceleration and reduces G and the potentially injurious forces acting on the spine (*Source:* John Martini, BRC).

Tolerance and Tolerance Limits

In its simplest form, human tolerance can be defined as the "ability to endure" without harm, or with acceptable harm. Human tolerance to transient acceleration can be defined in various ways. One useful and common approach is to determine a range of acceleration exposure that does not result in injury or death. The endpoint may be reached through various effects and at different levels for the whole body, or for specific body organs, structures, and systems.

There are three categories of impact. Whole-body impact is a generalized impact of the entire body as it occurs during an ejection or most laboratory tests. Penetrating impact is where an object penetrates a body part. Blunt impact is a focused nonpenetrating impact of a body part. Blunt impact and penetrating impacts may occur as a result of whole-body impact. Blunt, nonpenetrating impacts are common means of force application to restrained occupants of aircraft and spacecraft. Such forces are typically transmitted by seat surfaces, restraints, deforming cabin structures, and windblast. Localized blunt impact to inadequately restrained body parts may occur because of relative motion, which allows the body part to strike a fixed surface such as an instrument panel or a seat component. Therefore, whole-body acceleration effects, which involve generalized blunt impact, may secondarily include localized blunt impact.

Complex biological systems have multiple modes of injury. Most of the injury modes have little practical significance because the pathologic or lethal dose will be achieved by one mode before the others are reached at higher energy levels. In many cases a simple, single-degree-of-freedom model can be applied (60). In ejection seat design, such a single-degree-of-freedom model has been used to estimate the probability of injury in the lower spine. This injury normally occurs at a lower energy level than the energy required for other injuries.

Analysis of transient acceleration has been improved through research involving thousands of impact tests of human volunteers. The facilities now used for impact experiments include (i) towers that are used to drop test carriages onto decelerators such as metal-deforming devices or hydraulic cylinders, (ii) horizontal test tracks with various propulsion systems to propel test carriages into decelerators, and (iii) high-pressure gas actuators that accelerate a test carriage along either vertical or horizontal rails.

Comparison of test data collected from different impact facilities must be undertaken cautiously. Factors such as body support, restraint-system configuration, restraint pretension, subject bracing, prepositioning, waveform shape, and differences in data reference frames must be considered. The conditions imposed by the research device before the impact are critical (e.g., freefall tower vs. horizontal decelerator). When dynamic preloading, body positioning, muscle straining, and pretensioned restraints are employed, the results may not reflect actual in-aircraft results (61).

Summaries of portions of the historical tolerance database are available and can serve as useful guides to the literature (62,63). Extensive testing has also been accomplished using cadavers and anthropomorphic test devices (crash test dummies) and these results are also compiled in the database. The findings of these studies provide much useful information and insight (64). A brief summary is presented in the subsequent text.

Headward Acceleration ($+G_z$)

The limiting factor for exposure of humans to $+G_z$ impact is vertebral fracture(s) in the lower thoracic and/or the lumbar region. Early investigators estimated that acceleration levels of $+18$ to $+20$ G_z, with a velocity change of up to 17.5 m/s, could be tolerated without injury (65). USAF operational experience with ejection seats from 1949 to 1966 has shown that using these estimates as maximums for ejection catapult designs was reasonable, although not without injuries. For example, a review of 175 ejections from four aircraft producing peak acceleration levels of $+17.5$ to $+18.4$ G_z over 0.1 to 0.18 seconds, with velocity changes of 15.2 to 25.9 m/s, revealed a 7% incidence of vertebral compression fractures. A more comprehensive analysis of the larger set of operational data, using a single-degree-of-freedom model of the lower spine, led to the development of a method to estimate the probability of spinal injury during ejection (60).

Hard landings and crashes in helicopters have a greater component of $+G_z$ acceleration than the primarily $-G_x$ acceleration of fixed wing aircraft, and (as in all aircraft crashes) blunt trauma is the primary cause of death. The use of a shoulder harness affords protection against some injuries. In addition, in a survivable vertical impact, the use of a stroking crew seat has been shown to prevent spinal injury (66).

Footward Acceleration ($-G_z$)

Spinal injury is also the limiting factor for $-G_z$ when the applied acceleration is compressive, as in a headfirst water impact, but the area at risk is the neck. In a downward ejection seat, the resulting force is partly in traction, through the pelvis by the lap belt, and partly in compression, by the restraint shoulder straps. Under these conditions, volunteers have routinely tolerated half-sine wave acceleration profiles up to -10 G_z with times to peak acceleration ranging from 0.017 to 0.114 second and velocity changes of 1.5 to 15.4 m/s (67). Subjects in a rigid couch, restrained by two shoulder straps, a cross-chest strap, lap belt, crotch strap, and leg straps, tolerated peak accelerations up to -18.5 G_z with a velocity change of 5.94 m/s (68).

Transverse Rearward-Facing Impact ($+G_x$)

A restraining surface, such as a seatback, allows tolerance to very high onset rates when the acceleration vector is oriented in the +x axis. In aviation, this is most applicable to rear-facing occupants during a frontal crash. Beeding and Mosely exposed a subject to a peak acceleration of $+40.4$ G_x with a velocity change of 14.8 m/s and rate of onset of 2,139 G/s, with time to peak acceleration of 0.022 second, on a horizontal track decelerator. Special restraints and an element of dynamic preload were involved. Symptoms of shock, including loss of consciousness after the test, were experienced (69), but the subject survived.

Transverse Forward-Facing Impact ($-G_x$)

Perhaps the most dramatic human impact test experiences in any axis were those of Stapp and his colleagues, in a series of rocket sled studies published in 1951 (70). The highest acceleration exposure in this series was a $-45.4\ G_x$ run (45.4 G peak, $-37\ G_x$ average), with a velocity change of 54 m/s, which was experienced by Stapp himself in a forward-facing seat. The test had a G-onset rate of 493 G/s and included dynamic preload of the subject, specially designed wide belt restraints, and preimpact flexion of the neck. After this test, unilateral retinal hemorrhage occurred which resulted in a visual field defect lasting 10 weeks.

The most severe pathophysiologic effects in this group of experiments, however, were observed in a test involving another subject at the lower level of $-38.6\ G_x$, but at the considerably higher G-onset rate of 1,340 G/s. The subject experienced symptoms of shock, several episodes of syncope, and albuminuria for 6 hours. The limits of human tolerance in the −x axis are lower when the restraint system is less adequate, and in the absence of imposed dynamic preload.

Lateral Acceleration (G_y)

Subjects restrained only by a lap belt have been exposed to sideward impact up to 9.95 G_y, with a velocity change of 4.6 m/s (71). When a lap belt and double shoulder strap configuration was used, acceleration peaks up to 11.7 G_y, with a velocity change of 4.5 m/s, were tolerated (72). Earlier tests had been preformed using a vertical deceleration tower to explore the human response to y-axis impact. The subjects were restrained on their sides in an individually contoured couch. Tests were conducted on right and left lateral directions. Accelerations were varied from 4.3 to 21.6 G_y with impact velocities of 6.68 m/s. The test subjects' complaints and physiologic responses to these conditions suggested that neither subjective nor objective tolerance had been reached (73).

Multidirectional Acceleration

Efforts to determine human exposure limits for impact directions involving more than one cardinal axis have been limited to a narrow range of conditions, body support, and restraint systems. One multidirectional acceleration experiment was conducted using a vertical deceleration tower where the preimpact condition was near-weightless of freefall. A second experiment was performed on a horizontal deceleration track with a dynamic preload of approximately 0.3 G due to track friction.

In the first experiment, seven acceleration vectors were explored: up 45 degrees, up 45 degrees and right 45 degrees, up 45 degrees and left 45 degrees, right 45 degrees, left 45 degrees, left 90 degrees, right 90 degrees. Metal panels supported the subject's head, torso, and legs. Six acceleration profiles were used ranging from 3 to 26 G. Impact velocities ranged from 1.5 to 8.6 m/s with rates of onset from to 393 G/s to 1,380 G/s. Some temporary heart rhythm changes were noted immediately after four tests, but the tests were considered tolerable (73).

In the horizontal decelerator protocol, the subject experienced acceleration from 1 of 24 different directions. These compromised eight acceleration directions arrayed around the coronal plane, eight arrayed around a cone 45 degrees anterior to that plane, and eight arrayed in a cone 45 degrees posterior to the plane. Maximum repetitions ranged from 11.1 G for the −z axis to 30.7 G when the acceleration vector was acting from chest to back (−x axis) and 45 degrees left. Impact velocities were varied up to 13.7 m/s. None of these tests exceeded voluntary tolerance, but transitory postimpact bradycardia was a consistent finding for those impact vectors in which a component acted in the −z axis (74).

Useful data, which cannot be obtained from research on volunteer experimental subjects, have been gleaned from motor sport crashes since crash data recording was instituted in 2002 in the top three National Association for Stock Car Auto Racing (NASCAR) series race cars (75). Oblique frontal impacts have been experienced without serious injury when peak accelerations substantially exceeded those reported by Stapp, reaching 80 G but with a lower velocity change of approximately 34 m/s (76).

Impact Attenuation

Impact attenuation is accomplished when the forces transmitted between the acceleration source and the occupant are limited to less than the levels that would be experienced if the occupant was rigidly coupled to that source. The acceleration being transmitted to a vehicle occupant may be attenuated by vehicle structural deformation, impact-attenuation devices between the seat and the vehicle, body support and restraint materials, and impact-attenuating materials within equipment such as a flight helmet.

In a moderately severe crash, acceleration is attenuated by the energy required to deform or crush structural components. The attenuation provided by structural crush is a major factor in crash protection, because relatively large attenuation distances are available. Vehicles at risk of crashing vertically, such as helicopters, use seat-mounted impact devices intended to attenuate the acceleration of the vehicle (Figure 4-16). Energy storage and rebound is usually avoided by using viscous or friction damping, or by permanently deforming materials such as metal tubes or bands.

If the impact velocity exceeds the capability of the attenuation device, the stroke limit will be reached and the phenomenon of bottoming occurs. The acceleration of the occupant will increase until the velocity of the vehicle is reached, as demonstrated in the plots in Figure 4-17.

Commonly used impact-attenuation devices may also have other properties that limit their usefulness. Some employ force-limiting mechanisms, so that their performance will vary as a function of occupant weight. The degree of impact attenuation that can be provided by the body support and restraint system, or by padding that might be worn by

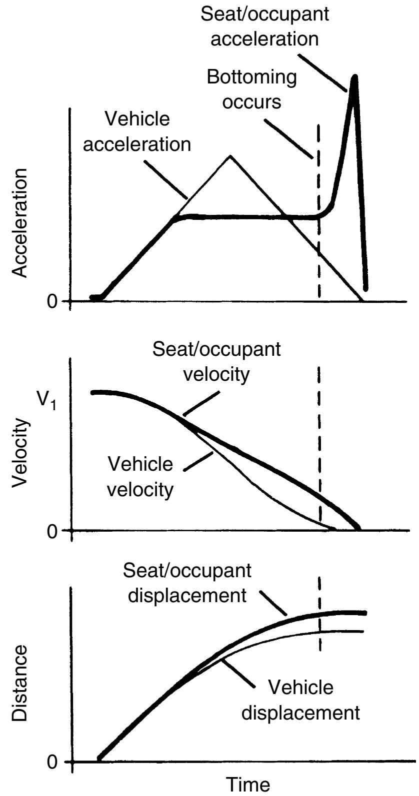


FIGURE 4-17 Bottoming. When the attenuation device capability is exceeded, bottoming occurs with the potential of very high acceleration and high forces occurring. Injury potential is therefore enhanced. These plots show subject and vehicle displacements, velocities, and accelerations during an impact. Note the high-G peak on the upper plot when bottoming occurs.

an individual, is typically limited by the small displacements that are available.

Restraints

The effectiveness of a restraint system depends on how well it transmits loads between the seat or vehicle structure and the occupant (while managing contact stresses). It also depends on the ability of the restraint to control the motion of restrained anatomic segments.

The first and most common restraint, the lap belt, provides a relatively low level of impact protection. The restraint loads are intended to be carried through the bones of the pelvis with the belt applied to the anterior superior iliac spines. If the belt is improperly tightened or positioned, or the acceleration vector is oriented to cause rotation of the pelvis, the belt can slip over the iliac crests to be against the abdomen. If this occurs, the belt loads will be applied against the lumbar spine with the abdominal organs interposed. When a lap belt is the only restraint, the most common injuries are the result of impact of the head and extremities within the vehicle.

The use of shoulder straps reduces the likelihood of an occupant striking the aircraft interior. In addition, they restrain forward movement of the torso during $-G_x$ acceleration, and may reduce the strike envelope for sideward and vertical impacts. The use of shoulder straps improves human tolerance to acceleration in any other direction by increasing the restraint-bearing area, increasing the number of anchor points for the torso mass, and reducing the relative motion between body parts. Where high upward acceleration components are anticipated, shoulder straps may help maintain the initial alignment of load-carrying spinal vertebrae.

Despite the advantages of shoulder straps, the tension loads create a potentially serious problem if they are attached to the center of the lap belt, as they are in many military harness configurations. These strap loads, developed under forward-facing impact conditions, lift the lap belt over the pelvis, allowing the belt to bear on the abdomen and the inferior costal margin. This problem has been observed in human tests at acceleration levels as low as 10 G with a velocity change of 5.5 m/s. Stapp reported that test subjects reached the threshold of voluntary tolerance with this restraint configuration at 17 G for impact velocities greater than 30 m/s (70). Some contemporary restraint harnesses include one or two straps that connect the lap belt buckle to the front central portion of the seat between the legs.

An example of a five-point restraint, currently in use in the space shuttle, is shown in Figure 4-18.

In view of the large influence that the restraint system has on tolerance to impact, the restraint configuration must be considered when interpreting human test results. For example, Stapp successfully demonstrated that humans are capable of tolerating acceleration levels up to $-45.4\ G_x$ in a forward-facing body position (70). The restraint system, however, was not a conventional military harness. A conventional military harness, composed of two 4.5-cm wide shoulder straps and a 7.6-cm wide lap belt, does not produce the effective coupling of various parts of the torso that the Stapp configuration provided. Unfortunately, a harness configuration of the type Stapp used has not been deemed practical in aerospace applications.

Efforts to develop a restraint system that will provide a high-bearing area and better control of body segment motion during impact have included the use of inflatable bags. This approach provides a restraint that does not encumber the vehicle occupant until the impact occurs. When predetermined acceleration levels are sensed on the vehicle structure, the airbag restraint is inflated by compressed gas, pyrotechnic gas generators, or a combination of the two systems. There has been concern that air bag deployments in aircraft could cause injuries due to interaction of the air bag with ancillary equipment such as night vision goggles (77). However, for crew positions not equipped with ejection seats, and for which head-mounted equipment is not used, inflatable bags may become practical.

Motor sport restraints typically include custom-fitted seats with multiple head and body side supports, side netting, helmets, head/neck restraints, and six- or seven-point restraint harness systems. Successful approaches have demonstrated reduction in neck tension load on the order of 80% as measured on test manikins (75). Some limitation in

FIGURE 4-18 This five-point restraint harness is currently in use in the space shuttle. Similar designs are found in both military and civilian aircraft (NASA).

head and neck mobility is typically imposed, and the devices are usually employed in conjunction with some head side and rearward supports, which also impose visual obstructions. Conceptually, the devices provide an alternate load path in tension that decreases the tension load in the neck during frontal impacts. Although the potential for improvements based on the design of these systems exist, their application in most aerospace settings will be limited by mobility issues, visual restrictions, and the costly need for custom fit.

Transient Acceleration Due to Escape Systems

The forces acting on the human body during emergency escape from high-speed aircraft include the thrust of the ejection seat catapult, the windstream surrounding the aircraft cockpit, the force exerted by the drogue parachute and the opening of the personnel recovery parachute. Ejection seats are complex mechanisms that need to balance a timely exit from the cockpit while avoiding excess accelerative forces.

Early ejection seats were propelled by cartridge-powered catapults to achieve seat trajectories that were adequate to clear the vertical tail of the aircraft and rescue airmen flying above 150 m. By the mid-1950s and early 1960s, rocket catapults were added to ejection seats. The objectives of the rockets were (i) to reduce spinal injuries by permitting the ejection cartridge thrust to be reduced and (ii) sustaining the thrust after cockpit separation to achieve trajectories that might provide escape from zero altitude and zero speed. (78) The 1950s and 1960s also saw the development of automatic ejection sequencing including barometric control of parachute opening, automatic restraint release, seat separators, and control of the parachute opening by staged reefing.

An out-of-position ejection (for example, leaning forward) may lead to vertebral injuries due to the catapult thrust. With a lower body weight, the overall weight of the seat and crewmember may be less than the original design specifications. In that case, at a given thrust, the G-level attained by a smaller crewmember may be greater than is required to clear the aircraft, and may be beyond safe limits.

For all crewmembers who experience an ejection, once the canopy is cleared, impact from windblast may cause severe or even fatal injury at high air speeds. The force associated with windblast is proportional to the square of air speed, so ejection at 600 knots presents a force that is nine times greater than an ejection at 200 knots. When the ejection airspeed is in the range of 500 to 600 knots, aerodynamic acceleration may be as high as 30 to 40 G for a typical human body and ejection seat.

Windblast may also cause injury to an unrestrained arm or leg. The limb is dislodged from its initial position by a combination of drag and lift (and especially sideward lift). Rearward motion of the limb, so-called flailing, results from the inequality between the ratio of its mass and aerodynamic drag and the ratio of the occupant/seat combination and aerodynamic drag.

The types of injuries observed as a result of high-speed ejection include scleral hemorrhage, fractures, joint derangements of limbs, and distraction of the cervical spine. Other injuries can occur due to direct impact with the seat or other hard structures. Recent estimates place 80% of ejections within the safe envelope. Sixty-two percent of ejectees had minor injuries whereas 16% had major injuries (79).

Seats and Seat Cushions

Aerospace designers have proposed that the ideal body support system is a rigid, individually contoured couch. This approach ensures that each external body segment will be simultaneously accelerated in the design direction, and that the support pressure exerted on the body surfaces will be minimized. Designs of this type have been found to be effective in laboratory impact, vibration, and centrifuge tests. The rigid contour approach was used in the Project Mercury astronaut couch design, and in the design of the seat and seatback used in Project Gemini. The disadvantages of the approach are the high cost of individual fitting and the discomfort of the rigid contour after a relatively short occupancy.

Attempts to circumvent the disadvantages of the rigid couch design have included the design of net couches. These designs provide improved comfort and avoid the high manufacturing costs of rigid contour couches. Thus far, net body support systems have been found to be effective in sustained acceleration, but have not provided good protection in either vibration or impact. The problem has been related to the elasticity of the net material. In both vibration and impact tests, the net body suspension system tended to resonate at or near the natural frequencies of the body.

The most successful body support systems that have aerospace vehicle applications have (i) slight contouring to control body position, (ii) dimensions that accommodate large variations in body size, (iii) relatively rigid, lightweight structures, (iv) padding to provide isolation from small-amplitude, high-frequency impacts and vibration, and (v) minimal cushioning of the seat to reduce flight fatigue without major degradation in impact protection. Armrests are often provided to increase comfort.

One might predict that materials and structures such as soft cushions should always protect an individual during an impact, but that is not the case. Rather than lessen forces, materials positioned between the occupant and the acceleration source can amplify the acceleration to which the occupant will be exposed. First, the materials may store energy during the impact and then release it in rebound. Therefore, the occupant is exposed to a larger velocity change than the vehicle. Second, these deformations may delay the acceleration of the occupant and create a large velocity difference between the occupant and the vehicle. The occupant acceleration must subsequently exceed the vehicle acceleration to eliminate the velocity difference. An ejection seat cushion is a common component that can cause this second problem by virtue of its stiffness and the distance it creates between the seat structure and the seat occupant.

It is important for such viscoelastic pads to impart minimal additional acceleration to the crewmember during ejection. A spongy, soft pad can result in severe impact damage to the vertebral column if the seat accelerates several inches before the compressing pad allows the occupant to be impacted from below by the seat. The initial movement of the seat must be simultaneous with movement of the occupant if the full protective effect of a rocket powered ejection is to be realized. The seat pads on ejection seats feel rather stiff and sometimes uncomfortable to aircrew. Life-support officers and flight surgeons should fully understand the potential ejection risks when a crewmember uses additional unauthorized padding.

One solution to the problem of ejection seat cushion comfort involves "rate-limited foams." Cushions made from this material slowly adapt to the pressure contour of the buttocks and provide comfort by eliminating "hot spots," but they do not compress quickly enough to bottom out during ejection acceleration (80).

Parachuting

In sport or operational use of parachutes, the opening force is transmitted to a parachutist through the risers and into the harness. It is of relatively long duration, on the order of 1 to 2 seconds at an altitude of 300 m. Parachute forces involve two phases, the first related to line stretch and the second to actual opening shock. The magnitudes of the forces are a function of variables that include deployment velocity, air density, deployment orientation of the canopy, suspension line length, and mass of the parachutist.

Opening shock may be high at high altitudes and/or high speeds. For example, a 91kg parachutist at equilibrium velocity using an 8.5-m diameter, flat-panel, nylon parachute, will experience a force of 6,200 Newtons (N) at an altitude of 2,100 m. Greater forces will occur at higher altitudes (e.g., 14,700 N at an altitude of 12,200 m) (81). Because the incorporation of automatic parachute opening devices that delay parachute opening until an altitude of approximately 4,600 m, and the use of parachute canopy reefing, injuries due to parachute opening have become uncommon.

After completion of the parachute opening sequence and descent to the Earth's surface, the parachutist confronts a final acceleration on ground impact. A typical military parachute will lower the parachutist to the Earth at a velocity of approximately 6.4 m/s. The landing impact is equivalent to that experienced after a jump from a height of 2.1 m. The resulting impact forces are a function of the effectiveness of the parachutist's fall technique (that is, the ability to use the legs as impact attenuators), and of the direction and velocity of horizontal wind drift.

Injuries due to parachute opening and landing falls from freefall bailouts are uncommon in typical sport parachuting use for several reasons. First, the velocity and altitude of parachute opening are more controlled. Second, skydiving techniques are used to control the parachutist's attitude at the time of opening. And third, steerable, gliding parafoil parachutes control landing altitude and final descent velocity.

Crashes

When an aircraft strikes an object or terrain, a force acts on its structure that compels it to decelerate. The magnitude of this force may be sufficient to slow the aircraft from its initial impact speed, to a final speed, which may be zero. The magnitude of this opposing force depends on the length of time it has to act. If the time is short, a higher force will result. If the time is comparatively long, the force will be less.

The potential for injury and death in a crash relate to the forces. As depicted in Figure 4-15A and B, when aircraft deceleration is spread over a longer distance, average G can be less and injury potential may be reduced. Equation 12 related the G of an occupant fixed at the center of the aircraft with the velocity at impact and the deceleration distance.

To assess injury potential in crashes, many investigators start by determining the variables of velocity and crash distance. Crash velocity can sometimes be determined from flight data recorders, inspection of flight instruments (e.g., marks on the airspeed indicator), or the flight characteristics of the aircraft at impact (e.g., a stall or spin). The crash distance can be determined from scene evidence that includes ground scars, aircraft crush, and seat stroking distance. A ground survey of the crash site and careful inspection of the wreckage can usually lead to reasonable estimates of this distance.

Equation 12 can then be used to develop an estimate of the *average* deceleration experienced by a person fixed within the aircraft. As discussed, the peak-G will be always be higher. Doubling the Equation 12 estimate is one approach to estimating peak-G. This assumes that the forces increased and decreased symmetrically during the crash and peaked in the middle. Other versions of Equation 12 have been developed that use different assumptions with regard to the timing of forces during the crash.

Because the estimated G is a vector, it must be reconciled with the position of the occupants within the aircraft, the flight path of aircraft, aircraft attitude, and other factors such as the slope of the impacted terrain. For example, a helicopter that autorotates and crashes will experience mainly vertically aligned forces. To a seated pilot, this would result in primarily $+G_z$. A person lying supine (like a medevac patient) would experience $+G_x$ in the same event. Reconciliation of the G-vector to each occupant of the aircraft is possible using trigonometry.

It is important to remember that Equation 12 is specific for an occupant fixed to the aircraft. This ideal never occurs in reality and, as discussed in the section on kinematics, occupant motion will always occur during a crash. This motion is influenced by the restraints, seats, and surrounding structures. Injury relates to the G and points of contact of the occupant with the aircraft. By estimating and understanding the G-vector of the crash, an understanding of this motion is possible.

With this understanding, assessment of injuries and the role of restraints and other safety devices in causing or preventing injuries can be made. If the initial estimate of G, including direction, falls well within a survivable range, and serious injury or death nevertheless occurred, the circumstances of the crash and design of safety equipment will merit special scrutiny.

Identification of injury mechanisms should meet the following criteria: (i) the load transmission path from seat structure and restraints to the point of injury should be understood; (ii) the load transmission path should be in accordance with physical principles by taking into account the origins of the loads, the motions of the transmitting structure under loading, and the capability of the transmitting structure to carry the loads; and (iii) the transmitted load should produce sufficient stress at the appropriate point to account for the injury.

Future Directions

Opportunities exist to enhance impact protection within the aerospace environment. One future challenge lies in the area of neck protection of crew wearing head-mounted equipment such as advanced optical displays, vision aids, and laser eye protection. These systems add weight and change the center of gravity of the head/helmet, which can significantly increase cervical stress during maneuvering acceleration, crash, or escape. A variety of alternate load path protective modalities for the head or helmet have been proposed. Some form of inflatable neck collar may offer potential benefit. Interventions being considered should be judged against the risks of what is emerging as a better understanding of injury criteria.

Other challenges include the need to clearly define gender differences in impact tolerance and impact protection requirements. Young adult females have an approximately 22% increased risk of death from matched vehicular crash forces (82). This challenge may be particularly relevant to space exploration and the expected forces that will be encountered during capsule recovery involving astronauts of both genders. Escape modules, including space capsules, can involve significant morbidity at ground impact after parachute descent (83).

Further efforts to provide personnel protection for military aviation should see the application of automated aircraft ground avoidance flight control systems, automatic ejection decision-making electronics, and the development and use of microprocessors designed to tailor the escape system performance to prevailing conditions. New technologies that will support such tailoring may include ejection catapults incorporating a dynamic preload phase (61), adjustment of ejection catapult thrust to accommodate different sizes of seat occupants, and parachutes with variable drag and lift characteristics.

Equipment worn by the occupant will become more complex and will integrate multiple functions including the anti-G suit, restraint, windblast protection, antiexposure provisions, environmental sensing, flotation, and protection from biological and chemical agents. The personnel protection ensemble and the means of emergency escape should be developed and tested as an integrated system to exploit potential synergies and avoid duplication and mismatches.

Several nations are currently engaged in the development of space vehicles that will carry crews into Earth's orbit, to the lunar surface, and in the case of the United States, interplanetary exploration. An issue that must be addressed more completely in these new space flight ventures is the influence of diminished bone and muscle strength on tolerance to abrupt acceleration after long-duration flights. The decision to retire the STS space shuttles and return to the capsule concept containing up to six crewmembers will provide significant design challenges over the next few years. The unprecedented number of crew in one capsule exposed to parachute recovery acceleration and landing impact will require concentrated and rigorous investigation and design.

With the advent of commercial space tourism, high-altitude military flight operations, and the near-term continued use of the STS space shuttle, the problem of high-altitude escape remains a challenge. Military aircraft capable of high altitude have employed ejection seats (with full pressure suits) and self-contained escape capsules. To escape the space shuttle, astronauts must unstrap from their seats, make their way to the main deck escape hatch, deploy a bailout pole, attach their parachute lanyard to the pole, and exit the craft. The system offers an escape option below 12,200 m altitude.

In the design of flight suits and anti-G garments for aircraft, it is important that inflated bladders are not used between the crewmember and an ejection seat. Helmets and clothing should be designed so as to not cause excessive lift and consequent injury at high air speed. For astronauts returning from ballistic or orbital flight, garments must serve the purpose of protection against loss of pressure and still be compatible with escape systems.

Lessons learned from earlier spacecraft designs may be applicable to these endeavors. Nevertheless, many design and personnel protection challenges remain, and several exist as a result of the multiuse of protective equipment that has been developed primarily for a different set of aerospace system design requirements. Pressure suits provide an example. A suit designed to provide protection within the context of a lifting body spacecraft design, where launch and entry accelerations are relatively low, may not be an appropriate design for a ballistic entry vehicle. Many aspects of a high-mobility suit, designed for space pressures, may not be appropriate during the higher accelerations associated with emergency egress during a flight, or during landing impact. These aspects may include the design of the helmet, the neck ring, or the difficulty of providing adequate torso restraint that is compatible with a full pressure suit. It will remain difficult to achieve a predictably successful protective system design, within a given design context, because so many factors must be considered. The relative importance of each factor may be perceived differently by vehicle designers and escape system designers.

Modeling and simulation will continue to evolve with improvements in computer microprocessors and memory. The automotive industry has taken the lead in the creation of human injury models and it may be possible to exploit these applications. These models are usually validated against cadavers or Anthropometric Test Devices. However, adjustment of injury parameters must be made for the different populations at risk as well as the differences in restraint, body support, and head protection. Because neither of these truly represents living people, use and application must be viewed with continued caution.

ACKNOWLEDGMENTS

The authors wish to acknowledge the important contributions of Sidney D. Leverett, James E. Whinnery, Russell R. Burton, and James H. Raddin, Jr. As authors of chapters on sustained and transient acceleration found in previous editions of this textbook, they provided much of the foundational content of this work. Mr. John Martini, an illustrator at Biodynamic Research Corporation, created and edited many of the figures and tables.

REFERENCES

1. Fryer DI. *Glossary of aerospace terms*. AGARDograph No 153. Aerospace Medicine Panel, 1971.
2. Gell CF. Table of equivalents for acceleration terminology. *Aerosp Med* 1961;32: 1109–1111.
3. Kaufman WC, Baumgardner FW, Gillingham KK, et al. Standardization of units and symbols: revised. *Aviat Space Environ Med* 1984;55: 93–100.
4. Wood EH, Sturm RE. Human centrifuge non-invasive measurements of arterial pressure at eye level during G_z acceleration. *Aviat Space Environ Med* 1989;60: 1005–1010.
5. Rossen R, Kabat H, Anderson JP. Acute arrest of the cerebral circulation in man. *Arch Neurol Psychiatry* 1943;50: 510–528.
6. Beckman EL, Duane TD, Ziegler JE, et al. Some observations on human tolerance to accelerative stress: phase IV. Human tolerance to high positive G applied at a rate of 5 to 10 G per second. *J Aviat Med* 1954;25: 50–66.
7. Wood EH. Some effects of the force environment on the heart, lungs and circulation. *Clin Invest Med* 1987;10: 401–427.
8. Banks RD, Gray G. "Bunt bradycardia": two cases of slowing of heart rate inflight during $-G_z$. *Aviat Space Environ Med* 1994;65: 330–331.
9. Banks RD, Grissett JD, Turnipseed GT, et al. The "push-pull effect". *Aviat Space Environ Med* 1994;65: 699–704.
10. Ryan EA, Kerr WK, Franks WR. Some physiological findings on normal men subjected to negative G. *J Aviat Med* 1950;21: 173–194.
11. Burton RR, Storm WF, Johnson LW, et al. Stress responses of pilots flying high-performance aircraft during aerial combat maneuvers. *Aviat Space Environ Med* 1977;48: 301–307.
12. Glaister DH. *The effects of gravity and acceleration on the lung*. AGARDograph 133. England: Technivision Services, 1970.
13. Burns JW, Ivan DJ, Stern CH, et al. Protection to $+12\ G_z$. *Aviat Space Environ Med* 2001;72: 413–421.
14. Shender BS, Forester EM, Hrebien L, et al. Acceleration-induced near-loss of consciousness: the "A-LOC" syndrome. *Aviat Space Environ Med* 2003;74: 1021–1028.
15. Burton RR. G-induced loss of consciousness: definition, history, current status. *Aviat Space Environ Med* 1988;59: 2–5.
16. Cochran LB, Gard PW, Norsworthy ME. *Variations in human G tolerance to positive acceleration* USN SAM/NASA/NM 001–059.020.10. Pensacola, 1954.
17. Code CF, Wood EH, Lambert EH, et al. Interim progress reports and concluding summary of 1942–46 acceleration physiology studies. In: Wood EH, ed. *Evolution of anti-G suits and their limitations, and alternative methods for avoidance of G-induced loss of consciousness*. Rochester: Mayo Foundation Special Purpose Processor Development Group, 1990: 409–430.
18. Navathe PD, Gomez G, Krishnamurthy A. Relaxed acceleration tolerance in female pilot trainees. *Aviat Space Environ Med* 2002;73: 1106–1108.
19. Heaps CL, Fischer MD, Hill RC. Female acceleration tolerance: effects of menstrual state and physical condition. *Aviat Space Environ Med* 1997;78: 525–530.
20. Hearon CM, Fischer MD, Dooley JW. Male/female SACM endurance comparison: support for the Armstrong Laboratory modifications to the CSU-13B/P anti-G suit. *Aviat Space Environ Med* 1998;69: 1141–1145.
21. Eiken O, Tipton MJ, Kölegård R, et al. Motion sickness decreases arterial pressure and therefore acceleration tolerance. *Aviat Space Environ Med* 2005;76: 541–546.
22. Tripp LD. *Use of lower body negative pressure as a countermeasure to negative G_z acceleration*. Wright-Patterson Air Force Base: United States Air Force, 1989.
23. Rushmer RF, Beckman EL, Lee D. Protection of the cerebral circulation by the cerebrospinal fluid under the influence of radial acceleration. *Am J Physiol* 1947;151: 355–365.

24. Banks RD, Grissett JD, Saunders PL, et al. The effect of varying time at $-G_z$ on subsequent $+G_z$ physiological tolerance (push-pull effect). *Aviat Space Environ Med* 1995;66: 723–727.
25. Goodman LS, Banks RD, Grissett JD, et al. Heart rate and blood pressure responses to $+G_z$ following varied-duration $-G_z$. *Aviat Space Environ Med* 2000;71: 137–141.
26. Goodman LS, LeSage S. Impairment of cardiovascular and vasomotor responses during tilt table simulation of "push-pull" maneuvers. *Aviat Space Environ Med* 2002;73: 971–979.
27. Kobayashi A, Tong A, Kikukawa A. Technical Note: pilot cerebral oxygen status during air-to-air combat maneuvering. *Aviat Space Environ Med* 2002;73: 919–924.
28. Rogers TA, Smedal HA. The ventilatory advantage of backward transverse acceleration. *Aerosp Med* 1961;32: 737–740.
29. Nolan AC, Marshall HW, Cronin L, et al. Decreases in arterial oxygen saturation and associated changes in pressures and roentgenographic appearance of the thorax during forward ($+G_x$) acceleration. *Aerosp Med* 1963;34: 797–813.
30. Clarke NP, Bondurant S, Leverett SD. Human tolerance to prolonged forward and backward acceleration. *J Aviat Med* 1959;30: 1–21.
31. Harding RM. *Survival in space: medical problems of manned spaceflight*. London and New York: Routledge, 1989.
32. Hershgold EJ. Roentgenographic study of human subjects during transverse acceleration. *Aerosp Med* 1960;31: 213–219.
33. Popplow JR, Veghte JH, Hudson KE. Cardiopulmonary responses to combined lateral and vertical acceleration. *Aviat Space Environ Med* 1983;54: 632–636.
34. Albery WB. Acceleration in other axes affects $+G_z$ tolerance: dynamic centrifuge simulation of agile flight. *Aviat Space Environ Med* 2004;75: 1–6.
35. Green ND, Ford SA. G-induced loss of consciousness: restrospective survey results from 2259 military aircrew. *Aviat Space Environ Med* 2006;77: 619–623.
36. Burton RR, Whinnery JE. Biodynamics: sustained acceleration. In: DeHart RL, Davis JR, eds. *Fundamentals of aerospace medicine*. Philadelphia: Lippincott Williams & Wilkins, 2002.
37. Lyons TJ, Craft NO, Copley GB, et al. Analysis of mission and aircraft factors in G-induced loss of consciousness in the USAF: 1982–2002. *Aviat Space Environ Med* 2004;75: 479–482.
38. Sevilla NL, Gardner JW. G-induced loss of consciousness: case-control study of 78 G-LOCs in the F-15, F-16, and A-10. *Aviat Space Environ Med* 2005;76: 370–374.
39. Michaud VJ, Lyons TJ. The "push-pull effect" and G-induced loss of consciousness accidents in the U.S. Air Force. *Aviat Space Environ Med* 1998;69: 1104–1106.
40. Mohler SR. *G effects of the pilot during aerobatics*. Washington, DC: Federal Aviation Administration, Office of Aviation Medicine, 1972.
41. Shender BS. Human tolerance to G_z acceleration loads generated in high-performance helicopters. *Aviat Space Environ Med* 2001;72: 693–703.
42. Drane M, Navathe PD, Preitner CG, et al. G-LOC in general aviation (abstract). *Aviat Space Environ Med* 2007;78: 225.
43. Wood EH, Satterer WF, Marshal HW, et al. *Effect of headward and forward accelerations on the cardiovascular system*. Wright-Patterson AFB, Dayton, Ohio: Aerospace Medical Laboratory, 1961.
44. Wood EH. Contributions of aeromedical research to flight and biomedical science. *Aviat Space Environ Med* 1986;57(Suppl 10): A13–A23.
45. Mikuliszyn R, Zebrowski M, Kowalczuk K. Centrifuge training program with "push-pull" elements. *Aviat Space Environ Med* 2005;76: 493–495.
46. Balldin UI, Werchan PM, French J, et al. Endurance and performance during multiple intense high $+G_z$ exposures with effective anti-G protection. *Aviat Space Environ Med* 2003;74: 303–308.
47. Laughlin HM. An analysis of the risk of human cardiac damage during $+G_z$ stress: a review. *Aviat Space Environ Med* 1982;53: 423–431.
48. AGARD Aerospace Medical Panel Working Group 18. Echocardiographic findings in NATO pilots: do acceleration ($+G_z$) stresses damage the heart? *Aviat Space Environ Med* 1997;68: 596–600.
49. Haswell MS, Tacker WA, Balldin UI, et al. Influence of inspired oxygen concentration on acceleration atelectasis. *Aviat Space Environ Med* 1986;57: 432–437.
50. Beyer RW, Dailey PO. Renal artery dissection associated with G_z acceleration. *Aviat Space Environ Med* 2004;75: 284–287.
51. Snyder QC, Kearney PJ. High $+G_z$ induced acute inguinal herniation in an F-16 aircrew member: case report and review. *Aviat Space Environ Med* 2002;73: 68–72.
52. Landau D-A, Chapnick L, Yoffe N, et al. Cervical and Lumbar MRI findings in aviators as a function of aircraft type. *Aviat Space Environ Med* 2006;77: 1158–1161.
53. Newman DG, Callister R. Analysis of the G_z environment during air combat maneuvering in the F/A-18 fighter aircraft. *Aviat Space Environ Med* 1999;70: 310–315.
54. Michaud V, Lyons T, Hansen C. Frequency of the "push-pull effect" in U.S. Air Force fighter operations. *Aviat Space Environ Med* 1998;69: 1083–1086.
55. Lyons TJ, Banks RD, Firth J. Introduction. *Human consequences of agile aircraft*,*RTO Lecture Series* 220, RTO-EN-12. Neuilly-sur-seine Cedex, France: Research and Technology Organization, 2000: I–1–I–9.
56. Buckey JC. Cardiovascular changes: atrophy, arrhythmias, and orthostatic intolerance. *Space physiology*. New York: Oxford University Press, 2006: 139–167.
57. Perez SA, Charles JB, Fortner GW, et al. Cardiovascular effects of anti-G suit and cooling garment during space shuttle re-entry and landing. *Aviat Space Environ Med* 2003;74: 753–757.
58. Stoll AM. Human tolerance of positive G as determined by the physiological end points. *J Aviat Med* 1956;27: 356–367.
59. Rogers, D. Model derived timing requirements for G_z protection methods. *Models for aircrew safety assessment: uses, limitations and requirements*. RTO Meeting Proceedings 20, RTO-MP-20. Neuilly-sur-seine Cedex, France: Research and Technology Organization, 1999: 22–1–22–6.
60. Brinkley JW, Shaffer JT. Dynamic simulation techniques for the design of escape systems: Current applications and future Air Force requirements. *Biodynamic models and their applications*. Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, 1971.
61. Hearon BF, Raddin JH, Brinkley JW. Evidence for the utilization of dynamic preload in impact injury prevention. *Impact injury caused by linear acceleration: mechanisms, prevention and cost*. AGARD Conference Proceedings No 322. AGARD-CP-322, 1982: 31–1–31–14.
62. von Gierke HE, Brinkley JW. Impact accelerations. In: Calvin J, Gazenko O, eds. *Foundations of space biology and medicine*, joint USA/USSR publication. Washington, DC: National Aeronautics and Space Administration, 1975: 214–246.
63. Snyder RG. Impact. In: Parker JF, Weeds VR, eds. *Bioastronautics data book*. NASA SP-3006. Washington, DC: National Aeronautics and Space Administration, 1973: 221–295.
64. Cheng H, Buhrman JR. *Development of the biodynamics data bank and the web user interface*. SAE 2000-01-0162. Warrendale: SAE International, 2000.
65. Lovelace W, Baldes E, Wulff V. *The ejection seat for emergency escape from high-speed aircraft*. ASTIA ATI, 7245, 1945.
66. Shanahan DF. *Basic principles of helicopter crashworthiness*. USAARL 93–15. Fort Rucker: United States Army Aeromedical Research Laboratory, 1993.
67. Brinkley JW, Getschow K. Escape system design criteria based on human response to -z axis acceleration. SAFE Association. 1988.

Data and paper available at: www.biodyn.wpafb.af.mil/GenStyInfo.asp?sn=198504.
68. Shulman M, Critz GW, Highly FM, et al. *Determination of human tolerance to negative impact acceleration*. UAEC-ACEL-510. Philadelphia: US Naval Air Engineering Center, 1963.
69. Beeding EL, Mosley JD. *Human tolerance to ultra-high G forces*. AFMDC-TN-60-2. Holloman Air Force Base: Aeromedical Field Laboratory, Air Force Missile Development Center, 1960.
70. Stapp JP. *Human exposures to linear deceleration. Part 2: the forward-facing position and the development of a crash harness*. Air Force Technical Report 5915. Wright-Patterson Air Force Base, Ohio: Aero Medical Laboratory, Wright Air Development Center, 1951.
71. Zaborowski AV. Human tolerance to lateral impact with lap belt only. *The eighth Stapp car crash and field demonstration conference*. Detroit: Wayne State University Press, 1966: 34–71.
72. Zaborowski AV. Lateral impact studies: lap belt-shoulder harness investigation. *The ninth Stapp car crash proceedings*. Minneapolis: University of Minnesota, 1966: 93–127.
73. Weis EB, Clark NP, Brinkley JW. Human response to several impact acceleration orientations and patterns. *Aerosp Med* 1963;34: 1122–1129.
74. Brown WK, Rothstein JD, Foster P. Human response to predicted Apollo landing impacts in selected body orientations. *Aerosp Med* 1966;37: 394–398.
75. Gramling H, Hodgman P, Hubbard R. Development of the HANS head and neck support for Formula One. *1998 Motor sports engineering conference proceedings*. SAE 983060. Warrendale, PA: Society of Automotive Engineers, 1998.
76. Melvin JW, Begemen PC, Faller RK, et al. Crash protection of stock car racing drivers—application of biomechanical analysis of Indy car crash research. *Stapp Car Crash J* 2006;50: 415–428.
77. Power ED, Duma SM, Stitzel JD, et al. Computer modeling of airbag-induced ocular injury in pilots wearing night vision goggles. *Aviat Space Environ Med* 2002;73: 1000–1006.
78. Anton D. Aviation: injuries and protection. In: Cooper G,ed. *Scientific foundations of trauma*. Oxford: Butterworth-Heineman, 1997: 172–188.
79. Hunt JC, Johanson DC. Ejection mortality and morbidity: what are the odds of being killed or injured during ejection? A first look, with trends. (abstract). *Aviat Space Environ Med* 2006;77: 322.
80. Hearon BF, Brinkley JW. Effect of seat cushions on human response to $+G_z$ impact. *Aviat Space Environ Med* 1986;57: 113–121.
81. Hallenbeck GA. *The magnitude and duration of parachute opening shock at various altitudes and air speeds*. ENG-49-696-66. Dayton, Ohio: Army Air Forces Materiel Command, Engineering Division, Aero Medical Laboratory, 1944.
82. Evans L, Gerrish PH. *Gender and age influence on fatality risk from the same physical impact determined using two-car crashes*. SAE 2001-01-1174. Warrendale: SAE International, 2001.
83. Hearon BF, Brinkley JW, Luciani RJ, et al. *F/FB-111 Ejection experience (1967–1980)—Part I: evaluation and recommendations*. AFAMRL-TR-81-113. Wright-Patterson AFB, Ohio: Air Force Aerospace Medical Research Laboratory, 1981.

RECOMMENDED READINGS

Buckey JC. Cardiovascular changes: atrophy, arrhythmias, and orthostatic intolerance. *Space physiology*. New York: Oxford University Press, 2006: 139–167.

Fryer DI. *Glossary of aerospace terms*. AGARDograph No 153. Aerospace Medicine Panel, 1971.

Glaister DH. *The effects of gravity and acceleration on the lung*. AGARDograph 133. England: Technivision Services, 1970.

Shanahan DF. *Basic principles of helicopter crashworthiness*. USAARL 93–15. Fort Rucker: United States Army Aeromedical Research Laboratory, 1993.

Stapp JP. *Human exposures to linear deceleration. Part 2: the forward-facing position and the development of a crash harness.* Air Force Technical Report 5915. Wright-Patterson Air Force Base, Ohio: Aero Medical Laboratory, Wright Air Development Center, 1951.

Wood EH. *Evolution of anti-G suits and their limitations, and alternative methods for avoidance of G-induced loss of consciousness*. Rochester: Mayo Foundation Special Purpose Processor Development Group, 1990.

CHAPTER 5

Vibration and Acoustics

Suzanne D. Smith, Jerry R. Goodman, and Ferdinand W. Grosveld

The authors dedicate this chapter to the late Dr. Henning von Gierke

Aerospace systems generate some of the most severe vibration and noise environments encountered by humans. These dynamic environments, either singly or in combination, threaten the comfort, performance, and psychological well-being of persons associated with or exposed to aerospace operations. In more severe and/or prolonged periods of exposure, these environments become a health or occupational hazard, causing serious degradations in performance, modifications of physiological functions, and injury, including chronic back pain and hearing loss. Although relatively simple and straightforward methods are used to control moderate vibration and noise, the development of more complex control and mitigation methods and procedures requires a more in-depth understanding of the mechanisms involved in the generation of undesirable symptoms. Human vibration and bioacoustic research have directed attention to delineating the psychological, physiological, and performance effects of vibration and noise exposures on humans. The extensive knowledge and databases gathered from these studies serve as the basis for exposure guidelines and standards and for the development of predictive tools for estimating the environmental effects. Technological advances in vehicle design and human-integrated equipment continue to challenge researchers, designers, and health experts in ensuring effective aircrew performance, communication, and occupant safety during vibration and noise exposures. A significant portion of this chapter is reflective of the basic tools and knowledge associated with human response to vibration and noise presented in previous editions that have not dramatically changed over time. This edition expands on the issues and problems relevant to current and future aerospace systems.

WHOLE-BODY VIBRATION IN AEROSPACE ENVIRONMENTS

General Vibration Terminology

Vibration

Vibration is oscillatory motion in dynamic systems. A dynamic system possesses mass and the capability for relative motion between parts of the system, having the property of elasticity. Oscillatory motion can include periodic motion, in which the motion repeats itself in a given time period, or aperiodic, in which the motion does not repeat itself. In its simplest form, periodic vibration can be described as sinusoidal motion. Aperiodic vibration includes shock or transient motions. Random vibration is a type of motion described by its statistical properties that never exactly repeats itself. Stationary random vibration is characterized by statistical properties that can be estimated to be time-invariant. Nonstationary random vibration changes with time and is unpredictable. Most vibration encountered in aerospace environments is aperiodic or random.

The dynamic system of concern is the human body. In aerospace operations, oscillatory motion in the human body can be generated through structure-borne vibration or airborne vibration. Structure-borne vibration results from contact of the body with a physical structure such as a vehicle floor, seating system, or other equipment. Airborne vibration results from contact of the body with sound pressure waves produced during the airborne transmission of acoustic energy (also referred to as *vibroacoustics*).

Frequency

For simple periodic or sinusoidal vibration, the frequency of the motion is defined as the number of complete cycles of motion occurring in a unit of time, usually 1 second. The reciprocal of the frequency is the period of the motion, or the time associated with completing one cycle. The international unit for frequency is the Hertz (Hz), which is one cycle per second. Random vibration is also described in terms of its frequency content or frequency spectra by using appropriate spectral analysis techniques.

Amplitude

Amplitude or intensity is the measure of the system oscillatory motion about a position of rest. The amplitude of vibration can be described as displacement, velocity, or acceleration. For translational vibration, displacement is expressed in the unit meter (m). Velocity is expressed in units of meters/second (m/s). Acceleration is expressed in units of meters per second squared (m/s^2). For rotational vibration, displacement is expressed in units of radians (or degrees). Velocity is expressed in terms of radians per second and acceleration is expressed in terms of radians per second squared. For simple sinusoidal motion, the relationships among displacement, velocity, and acceleration are:

$$\text{Acceleration magnitude} = -\omega^2 x(t) \text{ or } -(2\pi f)^2 x(t) \quad [1]$$

$$\text{Velocity magnitude} = \omega x(t) \text{ or } (2\pi f)x(t) \quad [2]$$

where ω is the angular frequency in radians per second, f is the frequency in Hz ($\omega = 2\pi$f), and $x(t)$ is the instantaneous displacement at time, t. The amplitude of a sinusoidal motion can be expressed as a peak or peak-to-peak value. However, with random vibration, a time-averaged or root-mean-square (rms) value is commonly used. The rms value is calculated as

$$X_{rms} = \sqrt{1/T \sum_{0}^{T} x^2(t)dt} \quad [3]$$

where x is the amplitude at time t, and T is the period of the vibration or length of time over which the rms value is being determined. The rms value of a sinusoidal motion is conveniently calculated as $1/\sqrt{2}$ or 0.707 times the peak value. Acceleration is the most common unit used to describe vibration or oscillatory motion, particularly with regard to human exposure, due to the widespread and convenient use of acceleration transducers for measuring the motion. Acceleration is sometimes expressed in terms of g or the acceleration resulting from gravity. One g is equal to 9.80665 m/s^2 depending upon the location on earth.

Resonance

When a sinusoidal excitation force is applied to a simple mass-spring-damper system (one degree-of-freedom), the system will initially vibrate at its natural frequency (free vibration), as well as at the frequency of excitation. When damping is present, the motion associated with the natural frequency will die out (transient motion) but motion at the excitation frequency will continue (steady state) as long as the force is present. If the excitation force is equal to the natural frequency of the system, resonance occurs. Without damping, the oscillations continue to build up, usually with catastrophic consequences. With damping, the oscillations will have finite amplitude. Resonance also occurs during exposure to random vibration that includes the natural or resonance frequency of the system. When the dynamic system is complex and described as a multi–degree-of-freedom system, each subsystem associated with a degree-of-freedom has the potential for excessive oscillations at its resonance frequency.

Direction

A body or system can move in translation, rotation, or a combination of both. Translational vibration occurs when a body or system oscillates along a straight line or in a linear direction (sometimes referred to as *rectilinear motion.*) The translational vibration of a body or system is defined along three perpendicular lines or orthogonal axes and include the fore-and-aft (X), lateral (Y), and vertical or longitudinal (Z) directions. Rotational vibration occurs when a body or system oscillates or rotates about a linear axis. Roll occurs when the body or system rotates about the X-axis, pitch occurs when the vibration is about the Y-axis, and yaw occurs when the rotation is about the Z-axis. The directions from which vibration enters the human body have been standardized by the International Standardization Organization [ISO 2631-1: 1997(E)] (1) and are illustrated in Figure 5-1. The human body is sensitive to the direction of vibration. Therefore, the perpendicular or orthogonal axes of vibration move with the body for movement from a seated or standing orientation to a recumbent orientation. The human body can translate and rotate either in or about a single axis or in a combination of up to six axes (X, Y, Z, roll, pitch, and yaw).

Spectrum

The spectrum of vibration represents the distribution of amplitude across frequency. This distribution is described in frequency bands that may be proportional or of constant bandwidth. The one-third octave bandwidth is the proportional bandwidth typically used when assessing human vibration exposure. Examples of constant bandwidths include spectra defined in increments of 0.1 Hz, 0.25 Hz, and

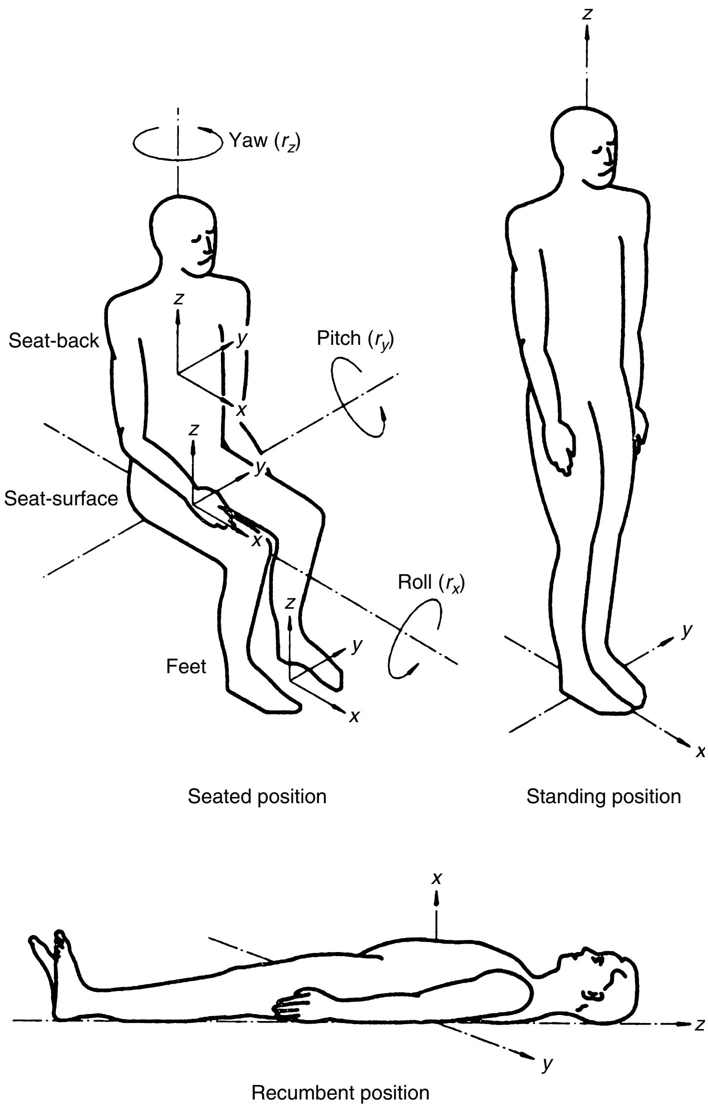


FIGURE 5-1 Basi-centric coordinate system of the human body. International Standards Organization (ISO). *Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements. ISO 2631-1:1997(E)*, 1997. [© ISO. This material is reproduced from ISO 2631-1 with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization (ISO). No part of this material may be copied or reproduced in any form, electronic retrieval system or otherwise or made available on the Internet, a public network, by satellite or otherwise without the prior written consent of the ANSI. Copies of this standard may be purchased from the ANSI, 25 West 43rd Street, New York, NY 10036, (212) 642-4900, http://webstore.ansi.org.]

0.5 Hz. The most common unit used to describe the spectral components associated with human vibration exposure is the root-mean-square acceleration in m/s^2 rms.

Duration

In general, human tolerance to continuous vibration declines with increasing duration of exposure. Although the time-dependent effects of vibration are still not fully understood, it is generally accepted that long exposures at higher vibration levels may present a health risk, particularly when the exposures occur repeatedly over long periods. The time-dependent effects form the basis for exposure criteria and standards as described later in this chapter.

Aerospace Sources of Whole-Body Vibration

Air Vehicle Propulsion System

The primary internal source of vibration in aerospace vehicles is the propulsion system. In conventional propeller-driven aircraft, vibration between 10 and 1,000 Hz is generated through the unbalanced forces associated with the engine speed and the propeller blade passage frequency. Blade passage frequency is calculated as the product of the propeller rotation speed (or propeller rotation frequency) and number of blades. In rotary-wing aircraft (rotorcraft) such as helicopters, propeller rotation speeds (or rotor speeds) range primarily between 200 and 400 revolutions per minute (rpm) or approximately 3 to 7 Hz. The numbers of blades typically range from two to four, producing blade passage frequencies mainly between 6 and 28 Hz, although higher blade numbers do exist. Blade imbalances can cause vibration at frequencies that are multiples of the propeller rotation speed, that is, 2 per revolution (2P), 3 per revolution (3P), and so on. Vibration can also be generated as multiples or harmonics of the blade passage frequency. Other propeller-driven aircraft have higher propeller rotation speeds and higher blade passage frequencies. For example, the six-bladed C-130J aircraft has a propeller rotation speed (or frequency) of 17 Hz. The blade-passage frequency is 102 Hz (6×17). Figure 5-2 illustrates the frequency spectra measured beneath the seat of a crewmember onboard a two-engine, four-bladed military propeller aircraft. The data were analyzed in 0.5 Hz increments. In this case, the propeller rotation speed (or

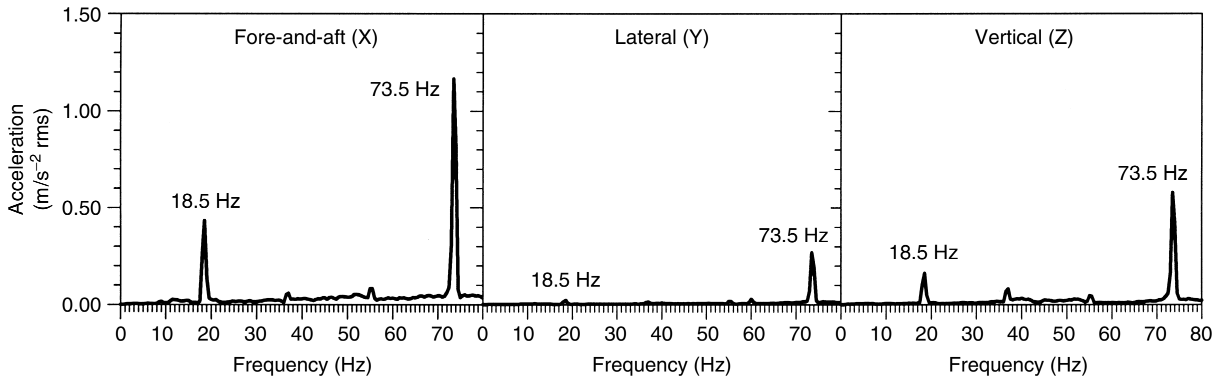


FIGURE 5-2 Example frequency spectra from a military propeller aircraft showing peak accelerations associated with the rotor speed propeller rotation frequency (~18.5 Hz) and blade passage frequency (~73.5–74 Hz).

frequency) was approximately 18.5 Hz, and the blade passage frequency was approximately 73.5 to 74 Hz. The structure-borne vibration generated at these frequencies is transmitted to the occupants through a seating system or other surface in contact with the body, can be felt by the occupant, and persists to varying degrees throughout the flight. Jet engines operate at higher speeds, minimizing the potential for generating low frequency, structure-borne vibration. In space vehicles, the primary internal source of vibration is combustion in the large, multistage rockets used to launch the vehicle.

During aircraft engine run-ups and ground-based maneuvering, ground operations and maintenance crews can be exposed to airborne vibration that is transmitted to the body through acoustic waves. The noise levels associated with airborne vibration can be substantial in military environments where ground crews are required to work close to powerful aircraft and in restrictive areas. Such a hostile vibration environment is also found on aircraft carriers.

Air Turbulence

Air turbulence is the major external source of structure-borne vibration in aerospace vehicles. Weather and thermal effects contribute to air turbulence during flights up to 10,000 m (32,808 ft). Wind shear occurring between moving air masses can cause clear-air turbulence at altitudes above 10,000 m. Ground turbulence, influenced by the local heating and cooling between the air and ground surface and by wind effects, is prevalent at altitudes below 500 m (1,640 ft). Ground turbulence is particularly important during tactical operations. Such operations can require the pilot to fly at low altitudes (below 500 m) at high speeds. Helicopters are affected by ground turbulence because they typically operate near the ground surface. In addition, vibration in these aircraft can also occur because of ground effects caused by the coupling between the downwash and rotating blades (2).

Air Vehicle Structural Resonance

Buffeting is the vibration of a vehicle as it interacts with the air in which it moves, generating aerodynamic forces on the structure. These forces can excite the various modes of vibration or resonances of the vehicle (including fuselage and wing bending). It is not uncommon to encounter buffeting during commercial jet aircraft flight because of bad weather, thermal disturbances, or clear air turbulence. Although occurring rarely, such vibration can be severe enough to affect control of the aircraft. Buffeting also occurs in military high performance jets during low-altitude, high-speed flight, and aerial combat maneuvers (ACMs). This low-frequency buffeting can be severe but short in duration. It can act as a control cue to the pilot during these maneuvers. However, the transmission of buffet vibration to the aircrew may cause involuntary motions in the body and affect the operation of critical equipment (3).

Space vehicles are affected by aerodynamic forces, particularly during the first few minutes of acceleration during launch. During launch, structural vibration can occur primarily between 2 and 15 Hz due to the excitation of lateral bending and longitudinal oscillatory motions (2). During reentry, the space vehicle is decelerated by atmospheric friction. Given modern day control systems, reentry into the earth's atmosphere is relatively smooth, although flight instabilities could cause relatively severe but short-term structural vibration (2).

Measurement and Analysis Techniques

Vibration Measurement Equipment

There are three components required to measure vibration: a transducer, signal conditioner or amplifier, and recording device. The transducer is an acceleration, velocity, or displacement detector that can measure the vibration in the various axes of translation and/or rotation. Accelerometers are the most commonly used transducers for measuring vibration because of their small size and light weight. Miniature accelerometers have been mounted onto major body anatomic structures such as the head. A semirigid disk with embedded accelerometers is commonly used to measure the vibration at the interface between the human body and contact surface, particularly in the seated position. The signal conditioner or amplifier is used to amplify the analog signal. Typically, the amplifier will produce an output in volts per unit of acceleration (when using an accelerometer). The signal conditioner may also be capable of filtering the analog signal to attenuate certain low frequencies (high pass filter) or high frequencies (low pass filter). Vibration signals are commonly converted to digital signals and stored on a digital tape recorder, computer, or other digital storage media.

A variety of vibration meters is available for evaluating human vibration exposure. The features of this equipment usually conform to vibration standards requirements for data collection, filtering, and processing. The vibration is typically collected at the interface between the human and contact surface as described in the preceding text.

Vibration Analysis

Spectral Analysis Techniques

Human vibration is typically evaluated as a function of frequency because the human body is very sensitive to the frequency of motion. Analog frequency or spectrum analyzers use calibrated narrow band, octave band, or fractional-octave band filters to estimate the spectral content of an analog time history signal. Digital spectral analysis uses the fast Fourier transform (FFT) to estimate the spectral content of a digital time history signal. The spectral density (also known as the *power spectral density* or *PSD*) is the mean square of the signal per unit frequency and is widely used to present and compare the frequency spectra of excited systems exposed to random vibration. When the measurement is acceleration, the units are $(m/s^2)^2/Hz$. The root-mean-square or rms value can be calculated by multiplying the mean square value by the width of the frequency band over which the measurement was integrated and taking the square root. Caution must be taken when applying the more common digital spectral analysis to estimate the spectral content. Digital signals are sampled at a defined sampling interval, Δ (seconds) or frequency, $1/\Delta$ (Hz). The Nyquist or folding frequency [$1/(2\Delta)$ Hz] is defined as one-half the sampling frequency ($1/\Delta$ Hz) and is the highest frequency that can be detected using the sampling interval, Δ (seconds). In order to avoid distortion or aliasing in the spectrum, the sampling interval should be small enough so that $1/2\Delta$ Hz is greater than the highest frequency component expected in the signal. When the highest frequency component in the measurement is unknown, antialiasing techniques are typically applied during processing of the data. There are several methods described in signal processing texts and computer software packages for estimating the power or autospectral density, as well as the cross-spectral density calculated between various measured responses of a system. It is cautioned that the application of analog or digital processing techniques assumes that the vibration can be approximated as stationary or time invariant.

Transfer Functions

The transfer function defines the vibration transmission characteristics of a physical system. The transfer function is used to characterize the input/output relations between the source of vibration and the excited system as well as the relationship between motions of coupled components composing the system. In this regard, it can be a useful tool for formulating and validating mathematical models of the system response and for developing mitigation techniques and processes. The simplest case for calculating any transfer function is with a single input and single output measured in the same direction. For random vibration, the transfer function can be calculated as the ratio between the cross spectral density of the output and input measurements and the auto spectral density of the input measurement. This method produces a transfer function that describes the linear relationship between the input and output. The coherence function is a calculated value between 0 and 1; the closer the value is to unity, the more linear the relationship between the input and output with less contributions from noise and other sources unrelated to the input vibration.

The single-input/single-output transfer function has also been used to estimate the transmission characteristics when there is vibration in more than one direction. Alternative analytic methods for estimating the multiaxis transfer matrix are described in textbooks on signal processing.

Two transfer function methods are typically used to describe the transmission characteristics and resonances of the human body. They are the driving-point mechanical impedance and transmissibility methods. Driving-point (mechanical) impedance is defined as the ratio between the measured transmitted force and the input velocity of a vibrating system occurring in the same direction and at the same location (usually at the interface where the vibration enters the body, i.e., seat or feet). The units for the driving-point impedance magnitude are Newton-seconds per meter (N-s/m). A related function, the apparent mass, is used by several investigators to reflect the biodynamic characteristics of the body. The apparent mass is the ratio between the transmitted force and the input acceleration.

Peaks in the driving-point impedance magnitude and the phase relations between the input and output provide information on the frequency range(s) in which maximum energy is transmitted to the human body (i.e., body resonances) and in which maximum physiological and psychological effects may occur. The driving-point impedance also provides quantitative information on the effects of certain conditions and equipment (posture, restraint, seats) and can be used as a first clue to the mechanical structure of the human body and how to describe that structure in mechanical and engineering terms. However, impedance is primarily affected by the response of major components of the system and those components located nearest to the driving point or measurement location. Transmissibility is the ratio between input and output measurements of the same units. The transmissibility method provides valuable information on the transmission pathways and has been historically calculated from the output acceleration measured at the head and the input acceleration measured at the point of contact with the vibrating surface (seat or feet). The transmission of vibration and impact through the body structure is of primary interest with respect to explaining undesirable effects such as trauma and performance degradation. Peaks in the magnitude of the transmissibility, like impedance, are associated with body resonances. Measurements at multiple locations can be used to estimate the resonance frequencies of system components and can, for the human body, provide coupling information between connected anatomic structures or regions. This information, as with impedance, is quite useful for developing and validating robust human vibration models (particularly mass-spring-damper or lumped-parameter models). For the human body, special consideration must be given to the weight, location, and method of attaching the transducer because these factors could affect the measurements.

Vibration Exposure Metrics

The transfer functions mentioned in the preceding text are used to describe the biodynamic responses of the human body. Characteristics of these responses are described in the section on **Vibration Effects on Humans**. There are human vibration standards that call for the use of specific metrics for assessing human exposure relative to health, safety, and comfort. The most common metric is the frequency-weighted rms acceleration. The acceleration is measured in all three orthogonal axes at the interfaces where the body contacts the vibrating structure. For the seated person, the interfaces include the surface between the buttocks and seat pan, the back and seatback, and the feet and supporting surface. For the standing person, the interface includes the feet and supporting surface. For the recumbent person, the interfaces include the pelvis and the supporting surface, and the head and supporting surface. A pliable disk with embedded accelerometers is typically used for these measurements. The measured acceleration is weighted in the time or frequency domain. In the time domain, the calculation is similar to Equation 3, where X_{rms} is now the weighted acceleration, a_w. Using the acceleration spectra (estimated using the spectral methods described previously), the weighted acceleration can be calculated as

$$a_w = \left[\sum_i (W_i a_i)^2\right]^{\frac{1}{2}} \quad [4]$$

where W_i is the frequency weighting associated with the *ith* frequency band, and a_i is the rms acceleration associated with the *ith* frequency band. The frequency weighting depends on the frequency, direction, and, in some cases, the location of the measurement. Historically, the frequency weighting curves were derived from equivalent comfort contours; the frequency weightings are high where the equivalent comfort contours are low (4). Researchers continue to evaluate human sensitivity to vibration. These efforts may result in a revision of the current frequency weightings. Additional manipulations of the weighted acceleration levels include the application of multiplying factors that reflect the relative effects of vibration direction, the use of the fourth-power instead of the second-power acceleration, and the vectorial summation of weighted acceleration levels for assessing vibration effects. Several of these metrics are described in the section on **Exposure Guidelines and Regulations**.

Vibration Effects on Humans

Human Body Biodynamics

The transfer function methods described earlier have been applied for characterizing human body biodynamics in vibration environments. Historically, most human whole-body vibration research and exposure assessments focused on measuring human responses during exposure to seated vertical vibration occurring along the vertical or longitudinal axis of the body (Z in Figure 5-1). The human body is most sensitive to vibration in the vertical direction. Some aerospace vehicles, such as propeller-driven aircraft and spacecraft, generate significant vibration in the horizontal directions. As mentioned in the previous section on vibration analysis, the two most common techniques used to evaluate the dynamic characteristics of the human body are the driving-point impedance (or apparent mass) and transmissibility.

Driving-Point Impedance/Apparent Mass

Figure 5-3 illustrates the driving-point impedance of one subject exposed to vertical vibration with several postures (5). At the low frequencies (below ~3 Hz), the body acts like a pure mass corresponding to the body weight (represented theoretically by the line $Z = m\omega$). Depending on the distribution of body mass and the associated composition, muscle tension, and posture, there is a major peak in the impedance that usually occurs between 4 and 8 Hz. This peak is known as the *primary whole-body resonance*. It is specifically associated with relative motions in the upper torso and shoulder girdle, including the soft tissue and organs in the upper thoracoabdominal region. These relative motions cause the transmission of higher forces back to the measurement site at the seat–occupant (or floor–occupant) interface as compared with the response of a rigid mass (Figure 5-3). At higher frequencies above the primary resonance frequency, more energy is absorbed by the elasticities and damping inherent in the soft tissues. At the higher frequencies, the impedance tends to decrease, although other smaller regions of resonance can be identified, particularly around 10 Hz and 15 Hz as shown in Figure 5-3. These peaks have been, in general, associated with resonances of the spine but may be influenced by the response of other anatomic structures, including the legs. Figure 5-3 shows that the sitting erect posture results in the upward shift of the resonance frequency by approximately 1 Hz. Using this simple representation, it can be shown that the erect posture results in stiffening of the body. The impedance of the human body is linear only to a first approximation. For simultaneous exposures to both vibration and sustained acceleration (inertial preload) at +2 G_z and above, the primary body resonance shifts to higher frequencies between 8 and 10 Hz with a corresponding increase in the magnitude of the impedance peak (6). The changes observed in body biodynamics and resonance behavior may also affect human tolerance (see section on **Physiology and Health**). However, any strong vibration occurring in the 8 to 10 Hz range could have more serious consequences during G-preload because of the shift in body sensitivity under these conditions. In contrast to the effects

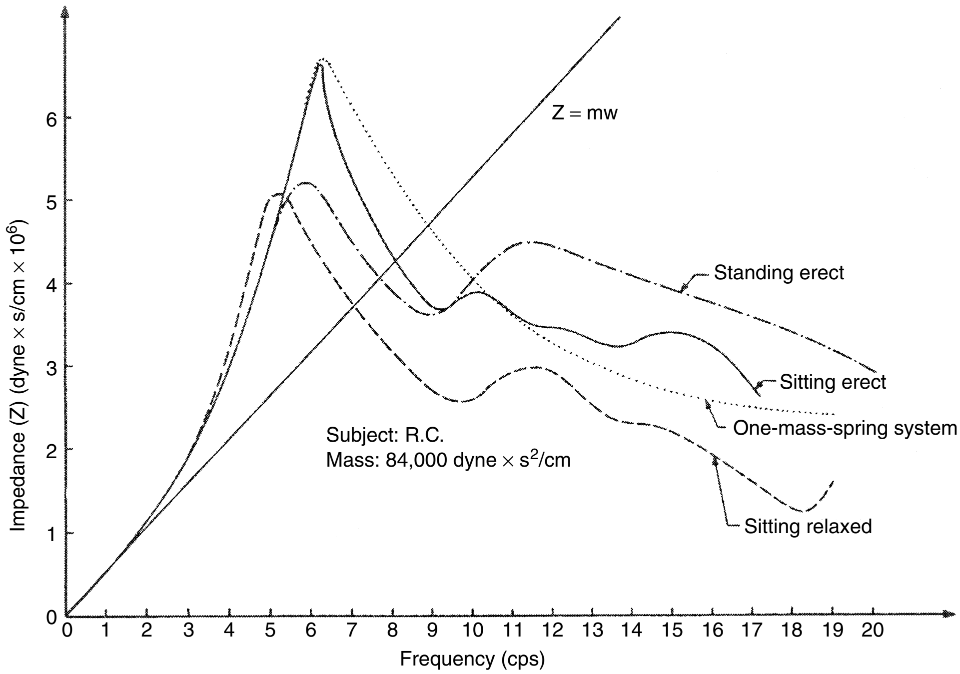


FIGURE 5-3 The modulus of the impedance of a subject at varied body postures compared with the impedance of a pure mass (mω) and a one-mass-spring system with damping. (From Coermann RR. *The mechanical impedance of the human body in sitting and standing position at low frequencies.* ASD technical report 61–492. Wright-Patterson Air Force Base, Ohio: Aeronautical Systems Division, Air Force Systems Command, United States Air Force, 1961.)

of sustained acceleration, studies have also shown that, under normal gravity, the primary resonance peak observed in the impedance shifts downward by 1 to 2 Hz with increases in the vibratory acceleration. The associated decrease in stiffness with higher vibratory acceleration is not as dramatic as the increase in stiffness associated with G-preload.

Transmissibility

The primary peak observed in the vertical seat-to-head transmissibility coincides closely with the primary resonance peak observed in the impedance data. The vertical head transmissibility decreases to relatively low values at higher frequencies above the whole-body resonance (when there is no direct contact with a vibrating surface). The transmissibility has also been calculated between the input at the seat and other body locations including the chest, spine, and legs (7). Caution should be taken in interpreting these results because the attachment of the transducer to the body surface may be affected by the response of the underlying muscle or skin. Accelerometers have become very lightweight and can minimize some of these effects. These data, along with the driving-point impedance data, provide valuable information on the coupling behavior occurring between anatomic regions. For example, the resonance peak observed in the impedance between 8 and 10 Hz for some subjects coincided with a peak transmissibility response in the unsupported legs (7). Peaks in the spine transmissibility have been observed around 6 Hz, 10 to 12 Hz, and 12 to 20 Hz, coinciding with peak regions observed in the impedance for some subjects and suggesting significant coupling effects between anatomic structures or regions.

Exposure to vertical axis vibration can result in other motions in the body depending on posture and head orientation. Head pitching in the forward-facing position is quite prevalent and is also observed during exposure to fore-and-aft vibration. Off-axis head orientations (other than the forward-facing position) can increase the transmission of vibration to the head. Head vibration can have significant effects on visual performance as discussed later in this chapter. In addition, resonance of the eye has been reported to occur between 20 and 70 Hz (4) and can contribute to visual degradation.

There have been an increasing number of women entering the predominantly male aerospace workforce (see Chapter 22). Because most subjects participating in research have been men, there is the need to understand similarities and differences in female/male responses to aerospace vibration for insuring optimum performance and safety of qualified individuals. Recent research has suggested that some differences may exist in the vibration response characteristics between women and men, but these differences have so far not resulted in definitive effects on performance, health, and safety relative to aerospace operations. The limited data have suggested that, in general, the distribution of the mass, stiffness, and damping characteristics of the major dynamic anatomic regions differs between women and men, but not to the extent of dramatically affecting the primary resonance frequency associated with upper torso motion (7).

Multiaxis Vibration

Although vertical vibration has been the major concern in aerospace operations, the presence of vibration in more than one direction can contribute to even greater and more complicated motions of the body. Research efforts to determine the effects of multiaxis or combined-axis vibration in aerospace operations are becoming more common with the availability of safe but sophisticated multiaxis vibration platforms and improved methods for quantifying occupant vibration during operations. As mentioned previously, there are analytic methods available for estimating the multiaxis transfer matrix when substantial vibration occurs in more than one axis.

Airborne Vibration

The mismatch between the acoustic impedance of air and the human body surfaces prevents significant amounts of acoustic energy from entering the body, particularly at higher frequencies (8). With decreasing frequencies below 1,000 Hz, more acoustic energy is absorbed in the form of transverse shear waves. With exposure to high-intensity noise levels (120 dB) between 100 and 1,000 Hz, tissue vibration occurs and the noise is felt through the stimulation of somatic mechanoreceptors (2). Below 100 Hz, intense noise can cause whole-body vibration that not only affects motion in the chest, abdominal wall, viscera, limbs, and head but can also generate motions in the body cavities and air-filled or gas-filled spaces (2). Von Gierke reported that resonance of the chest wall and air-filled lungs occurs around 60 Hz (8).

Previous studies investigating the effects of airborne vibration have directed attention to the association between noise level and the subjective assessment of the exposure (9). Lightweight accelerometers have been attached to the body surface for estimating body accelerations while standing near jet aircraft during engine run-ups (10). Figure 5-4 shows peak acceleration in the upper torso between 60 and 100 Hz, particularly in the fore-and-aft (X) direction of the chest for one subject. This peak coincides with the upper torso resonance reported by von Gierke and Nixon (8). It also appears that, under the conditions tested, the peak increases with increasing noise level. It should be cautioned that these preliminary data do not address the effects of airborne vibration on individuals of varying weight and stature.

Physiology and Health

The mechanical stresses imposed on the body during vibration exposure can potentially lead to interference with bodily functions and tissue damage in practically all parts of the body, depending on the frequency range and exposure conditions. Most aerospace vibration exposures remain below injury levels. Acute exposures to whole-body vibration, primarily in the range of 1 to 20 Hz (11), of intensities voluntarily tolerated by human subjects up to the limit of severe discomfort or pain, have not resulted in demonstrable harm or injury. Continued exposures at the limits of tolerance are considered to have a high potential for producing bodily damage. Figure 5-5 illustrates the short time, 1-minute, and 3-minute tolerance limits reported by healthy adult male subjects exposed to vertical sinusoidal vibration (11). The figure shows the decrease in tolerance with longer exposure periods. Minimal tolerance occurs between 4 and 8 Hz, the frequency range associated with whole-body resonance. Figure 5-6 depicts the frequencies at which the most severe symptoms have been reported. Headache is often associated with exposure to frequencies above 10 Hz. Particularly for exposures to sustained fore-and-aft acceleration (G_x) with g_x or g_y vibration (space couch positions), motions are transmitted to the head directly from the headrest, which can lead to extremely uncomfortable and disturbing impacts to the head. During launch and reentry of spacecraft, the crew is oriented in the semisupine posture. This minimizes the influence of sustained acceleration by directing the force through the fore-and-aft or X direction of the body (Figure 5-1). This does couple the body more closely to the seating system. The vibration tolerance associated with this seat orientation is discussed in the section **Human–Equipment Interfaces**.

Most physiological effects in the 2 to 12 Hz frequency range are associated with the resonance of the thoracoabdominal viscera. Movement of the thoracoabdominal viscera

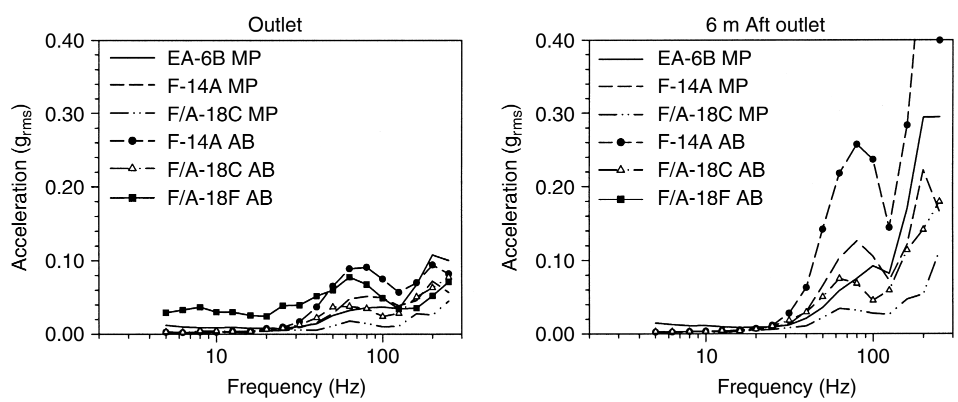


FIGURE 5-4 Acceleration peak observed between 60 and 100 Hz measured in the fore-and-aft direction of the chest during ground engine run-up tests in selected aircraft at military power (MP) and afterburner (AB). (Smith SD. The effects of airborne vibration on human body vibration response. *Aviat Space Environ Med* 2002;73(1):36–45.)

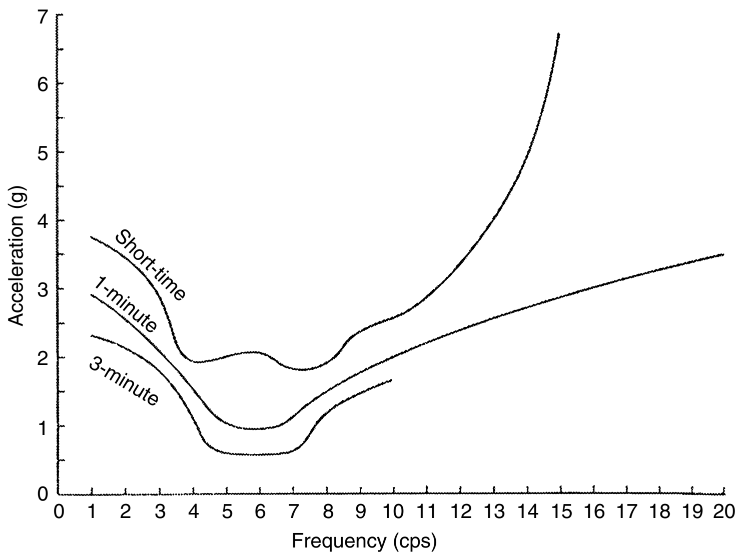


FIGURE 5-5 The short-time, 1-minute, and 3-minute tolerance limits reported during vertical sinusoidal vibration. cps, cycles per second or Hertz. (Magid EB, Coermann RR, Ziegenruecker GH. Human tolerance to whole body sinusoidal vibration. *Aerospace Med* 1960;31:915–924.)

in both X- and Z-axis excitation is responsible for the interference of vibration with respiration. It causes the involuntary oscillation of a significant volume of air in and out of the lungs, leading to an increase in minute volume, alveolar ventilation, and oxygen consumption. In experimental exposures to g_z vibrations, pCO2 decreased and clinical signs of hypocapnia were observed, suggesting hyperventilation (2). As shown in Figure 5-6, dyspnea results from short exposures to high-amplitude vibration. Changes in cardiovascular functions, including arterial blood pressure, cardiac index, heart rate, and oxygen consumption index, were shown to be dependent on the amplitude and the frequency of whole-body vibration. In general, the combined cardiopulmonary response to vibration in the 2 to 12 Hz range resembles the response to exercise. Although increased muscular effort of bracing against the vibration and psychological factors may account for some of the response, observance of the same general pattern in anesthetized animals speaks for the stimulation of various mechanoreceptors (12).

The most commonly reported chronic health symptoms in occupations that include prolonged whole-body vibration exposure are back pain and back disorders. However, these symptoms are also reported for other occupations as well. The spinal column is a major pathway for the transmission of vibration in the upper torso. Repeated exposures to vibration can affect the mechanical integrity of the musculoskeletal components, leading to injury. In aerospace operations, the highest incidence of back pain and back disorders is reported

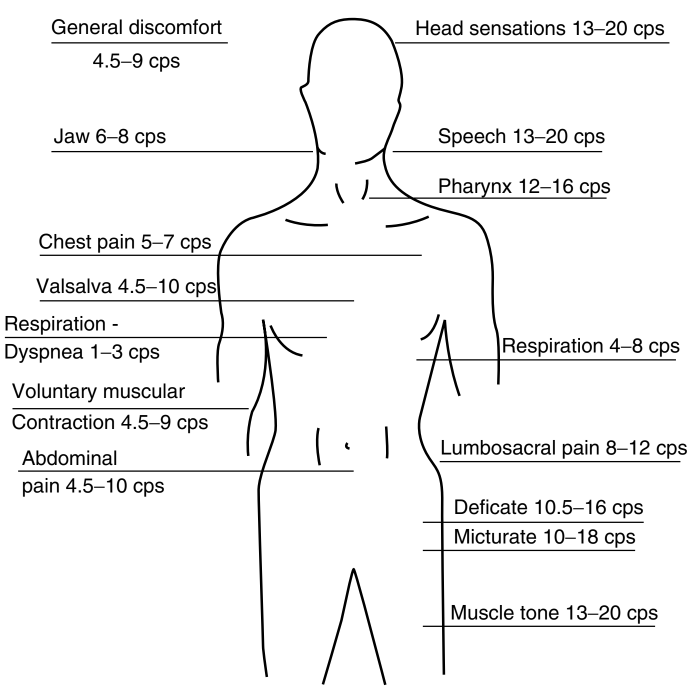


FIGURE 5-6 Symptoms experienced for frequencies between 2 and 20 Hz at tolerance levels. cps, cycles per second or Hertz. (Magid EB, Coermann RR, Ziegenruecker GH. Human tolerance to whole body sinusoidal vibration. *Aerospace Med* 1960;31:915–924.)

for helicopter pilots. Body posture is an important factor to consider in the generation of these symptoms. Helicopter pilots in particular may adopt poor sitting postures to operate the aircraft and to improve visibility (13,14).

The symptoms of subjects exposed to airborne vibration were studied by the U.S. Air Force in the 1960s (9). In summary, for exposures below 150 dB, the most common symptom reported was mild-to-moderate chest vibration. From 50 to 100 Hz, pure tone exposures reached levels above 150 dB. Voluntary tolerance was reached at 50 Hz (153 dB), 60 Hz (154 dB), 73 Hz (150 dB), and 100 Hz (153 dB) based on the significance of symptoms reported by the subjects. Symptoms included headache (50 Hz); coughing, severe substernal pressure, choking respiration, salivation, pain on swallowing, hypopharyngeal discomfort, and giddiness (60 Hz and 73 Hz); and mild nausea, giddiness, subcostal discomfort, cutaneous flushing, and tingling (around 100 Hz) (9). In the more recent study (10), reports of increasing chest vibration coincided with the increase in the peak chest acceleration and the increase in the noise level. It has been suggested that prolonged exposures to high-pressure, low-frequency noise may have physiological and pathological consequences.

Performance

Manual Control and Head Tracking

Low-frequency aerospace vibration that occurs during turbulence or buffeting in jet aircraft, helicopter operations, and launch and reentry of space vehicles present a particular challenge to manual control and head tracking performance. The involuntary motions of the body and the extremities introduced by the vibration are imposed as disturbances on the required control of the human operator. The greater the vibration amplitude of the hand, foot, or head in comparison with the required control motion (through strong original excitation or through resonance reinforcement), the larger the undesirable interference.

Laboratory manual control experiments have shown that manual tracking errors increase in the 2 to 16 Hz frequency range at seat accelerations above approximately 0.05 g_z rms. The maximum decrement is usually in the range of 4 Hz, which is in the vicinity of the main body resonance (4 to 8 Hz). Above approximately 0.25 g_z rms, manual control can be seriously affected and worsen with time due to fatigue (2). For X-axis and Y-axis vibration, the largest decrements are at 1.5 to 2 Hz. Caution should be taken in generalizing the decrements because they depend too much on the specific details of the control task (e.g., position, velocity or force control, amplitude of required control motion) and the hand-arm or foot-leg support. Early studies suggested that high-intensity noise between 100 and 105 dBA combined with vibration produced less decrement in manual tracking performance than with vibration alone. However, when 110 dBA noise was combined with vibration, the tracking performance was more degraded than observed for either noise or vibration alone (15).

The advent of helmet-mounted equipment requires the head to track and target objects. Low-frequency vibration that causes oscillations of the head can increase tracking and targeting error. Off-axis head orientations can further increase head motions and have been associated with increased head tracking error below 10 Hz (16).

The severity of the vibration interference can be influenced to some extent by the operator's control strategy. For example, under turbulent flight conditions, pilots often postpone manual activity during short bursts of high-amplitude vibrations and introduce corrective action as soon as the burst is over. Under sustained turbulence, very low frequencies can excite "pilot-induced oscillations," which are caused by inappropriate control inputs. The pilot apparently has time to correct for the disturbance inputs but, owing to misinterpretations of kinesthetic cues or the response characteristics of the motor system, he or she does not compensate in an appropriate way at some frequencies and adds to aircraft instabilities.

Visual Performance

A complex relationship exists among all of the relevant parameters affecting visual performance including vibration frequency, amplitude and direction, viewing distance, illumination, contrast, the shape of the viewed object, and the occupant posture and restraint. Difficulties in reading instruments and performing visual searches occur when vibration introduce relative movement of the eye with respect to the observed object or target, even when the observed object (such as the instrument panel) is excited by the same structural vibration. The greatest decrement in visual performance occurs with vibration of the object or display alone, followed by vibration of the occupant alone. The least relative effect occurs with vibration of both the occupant and the object or display (4).

Compensatory eye movement is the physical response to vibration and affects visual performance. During head rotation, the vestibulo-ocular reflex causes the eye to move in the opposite direction of the motion, thereby stabilizing the line-of-sight (LOS) to a stationary object (compensatory eye movement). The compensatory eye movement has been shown to be effective up to 8 Hz with some studies showing effectiveness up to 20 Hz (4). Compensatory eye movement is the most effective during head rotations. Exposure to translational vibration at lower frequencies is expected to produce both translation and rotation of the head. At higher frequencies, the eye resonance described previously can result in blurred vision. Given the damping effect of the body at higher frequencies, this effect may occur only where high levels of vibration are present or when the head comes in direct contact with a vibrating surface.

The launch and reentry phase of spaceflight presents a unique problem for visual performance because the crew is oriented in the semisupine posture with both body and head closely coupled to the seat and restraint system. This special case is discussed further in the section **Human–Equipment Interfaces**.

Cognitive Performance

Early studies strongly suggested that the performance of simple cognitive tasks (pattern recognition and monitoring of dials and warning lights) were not affected by vibration. More demanding tasks have shown to be affected by vibration and combinations of vibration and noise. One study involved mental arithmetic and short-term memory during a 0.5 g_z (peak) vibration at selected frequencies between approximately 5 Hz and 16 Hz. The results showed significantly slower performance as compared to the static condition (17). Regardless of these findings, it has also been suggested that vibration can increase the level of arousal, similar to observations in noise, depending on the exposure intensity, exposure time pattern, and the subject activity.

As with manual tracking performance, studies have also been conducted on the combined effects of vibration and noise on cognitive performance. An early study suggested that either 100 or 110 dBA noise combined with vibration produced more adverse effects on the performance of a mental arithmetic task than either stressor alone. In another study using a complex counting task, it was found that the effect of noise was reversed with vibration. While 100 dBA noise as compared to 65 dBA noise produced greater performance degradation, the 100 dBA noise combined with vibration as compared to the 65 dBA noise combined with vibration produced less degradation (15). These results were similar to the results for manual tracking performance using similar noise levels.

Human-Equipment Interfaces

In aerospace operations, the human body becomes coupled with any interfacing equipment, including seating systems and helmet systems. Although this coupling could provide the mechanisms for minimizing vibration effects, current use of this equipment in aerospace environments has been associated with comfort, health, and performance degradation, exacerbating effects already described previously. For example, most conventional seat cushions tend to increase the transmission of vertical vibration from the seat to the upper torso and head in the vicinity of whole-body resonance (4 to 8 Hz), but dampen these motions at higher frequencies as compared to sitting in a rigid structure. Passive suspension systems have been used to attenuate vehicle vibration near human resonance but typically increase the transmission of vibration to the body at around 2 Hz and below, producing relatively large displacements at these frequencies. Active suspension systems use a feedback mechanism to stabilize the seat motion relative to the vehicle motion. In military aircraft that include ejection seats, the seat cushions are relatively thin and stiff, to minimize any rebound of the body during ejection or ground impact. Consequently, they provide little damping or isolation from any vehicle vibration. Current suspension or isolation systems may add unwanted weight and compromise crashworthiness in these types of aircraft. As mentioned previously, vibration transmitted directly from the headrest to the head can affect visual performance, causing visual blurring most likely related to eye resonance.

Helmet systems used in military flight environments can affect head motions. Increasing the mass of the helmet and increasing the distance between the center of gravity (CG) of the head/helmet system and the head have been shown to increase head pitch in the forward-facing direction (18). Sophisticated helmet-mounted visual systems including night vision goggles (NVG), helmet-mounted displays (HMDs), and helmet-mounted targeting and display (HMT/D) interfaces present unique issues in performance. For example, the compensatory eye movement is rendered ineffective in stabilizing the LOS to a viewed object when using an HMD because of the movement of the projected object with the head (19). It has been shown that reading error is greater with the use of an HMD as compared with a panel-mounted display (4). Relative head/helmet motion or slippage could further reduce the effectiveness of these systems. As mentioned previously, degradation in head tracking performance has also been associated with vibration (3,16). The low-frequency buffeting associated with maneuvering of certain fighter aircraft can cause substantial involuntary motions of the head and may compromise the performance of head tracking and targeting systems. The extreme head/helmet orientations that can occur during these operations exacerbate this issue.

The vibration encountered during launch and reentry of spacecraft presents a special case for human tolerance and visual performance in the semisupine posture, where coupling between the occupant and seating system is critical. Studies were conducted back in the 1960s to evaluate the effects of the seat or couch, body restraint, and head restraint on subjective tolerance and visual performance. Figure 5-7 illustrates the mean level of acceleration tolerance at the tested frequency for the seat or couch configurations (20). The exposure duration depended on the frequency; the higher the frequency, the less time to reach a given acceleration level. The longest tolerance exposure took 250 seconds or approximately 4 minutes. There was no helmet or head restraint used with the contoured couch. The subjects maintained their head in the headrest. If head buffeting became intolerable, they could lift their head and continue until voluntary tolerance was reached. A helmet system with restraint in the X and Y directions was used with the adjustable couch. The helmet restraint release was designed into the system. Once the subject released the helmet restraint, the exposure was discontinued and the associated acceleration level considered the voluntary tolerance. Figure 5-7 shows that the adjustable couch produced higher tolerance in the X-axis below approximately 10 Hz but flattened at higher accelerations, low tolerance in the Y-axis above approximately 8 Hz, and similar tolerance as compared to the contoured couch in the Z-axis. In the X-axis, the main focus of complaints was in the thoracic area, particularly with the contoured couch. The subjects reported difficulty breathing with both configurations. Repeated impact of the sacrum was reported for the adjustable couch, although, in general, the body was more coupled to this couch as compared to the contoured couch. These symptoms were

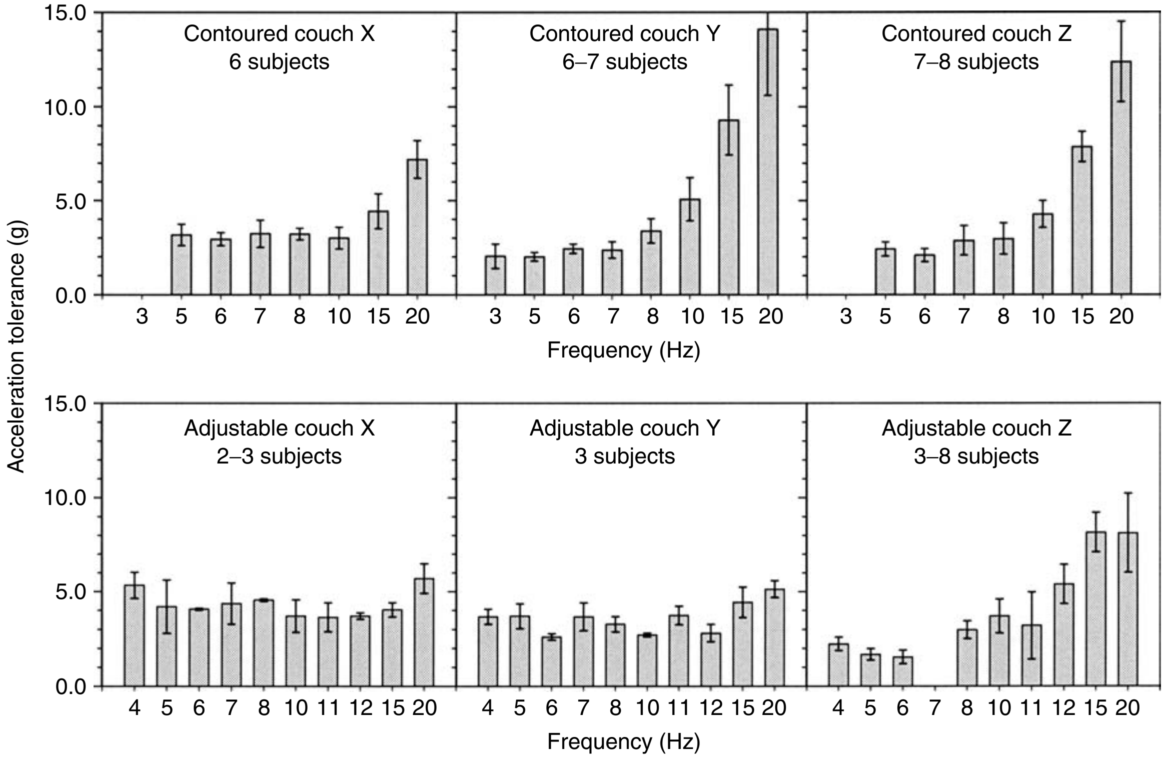


FIGURE 5-7 Mean level of human acceleration tolerance for two spacecraft couches. Tolerance is shown for the three orthogonal directions of the recumbent occupant (Figure 5-1) at selected frequencies. (Redrawn from data presented in Temple WE, Mandel MJ, Clarke NP, et al. *Man's short-time tolerance to sinusoidal vibration. AMRL-TR-65-96*, Wright-Patterson AFB, Ohio: Aerospace Medical Research Laboratories, 1965.)

also reported for the Y-axis, but not as frequently. Frictional rubbing and banging were reported for the contoured couch in the Y direction. In the Z-axis, there were more complaints about the head, including headache and sore neck muscles. Raising the head appeared to isolate the head from higher frequency vibration in the contoured couch, but may have contributed to fatigue. The helmeted head and good coupling to the adjustable seat limited complaints at low frequencies but reduced tolerance at higher frequencies, particularly in the horizontal directions (20).

Dial-reading performance was investigated at 6, 11, and 15 Hz using a Mercury helmet (21,22) and Apollo helmet (23) in the semisupine posture. The Mercury helmet was tested in the X ($+1\ G_x \pm 1.1\ g_x$) and Y ($+1\ G_x \pm 0.9\ g_y$) directions in the first study and only in the X direction in the second study. The Apollo helmet was tested in both the X and Y directions at levels coinciding with those used in (21). The first study (21) included the unrestrained and restrained helmeted head. The second study (22) included the restrained head and a piston-spring damper. The third study (23) tested the helmet with and without a liner. In general, all three studies showed that coupling the head to the seat reduced the reading error at frequencies below 10 Hz. This also coincided with the increase in tolerance when restraining the head (20). The results suggested that isolating the head at frequencies above 10 Hz might improve reading performance and improve tolerance (22). It is cautioned that the early tolerance and performance studies were conducted in well-controlled laboratory environments with physically qualified military members.

Vibration Protection and Mitigation

Exposure Guidelines and Regulations

National and International Standards

Given the physiological and psychological effects of vibration described previously, it is clear that there are no simple assessment procedures and exposure limits that are applicable to all environmental, human posture and restraint, and task performance conditions. However, based on laboratory and field experiences, whole-body vibration standards have been developed that provide boundaries and guidelines for assessing the effects of vibration. The primary national standard for structure-borne vibration is the American National Standards Institute (ANSI) *Guide for the Evaluation of Human Exposure to Whole Body Vibration* (ANSI S3.18–2001) (24). The primary international standard is the International Standards Organization's (ISO) *Mechanical Vibration and Shock: Evaluation of Human Exposure to Whole Body Vibration, Part 1: General Requirements* (ISO 2631-1: 1997) (1). The 2001 ANSI standard is identical to the ISO 2631-1: 1997.

The ISO 2631-1: 1997 uses the frequency-weighted accelerations and multiplying factors described in the section

Vibration Analysis for assessing the effects of vibration. For assessing the effects of vibration on health, the ISO 2631-1: 1997 provides health guidance caution zones as shown in Figure 5-8 (based on Equation B.1). Below the lower boundary zone, health effects have not been clearly documented or observed. Within the upper and lower boundary zones, caution is indicated for potential health risks. Above the higher boundary zone, health risks are likely. The highest rms value of the frequency-weighted acceleration determined in any axis at the seat pan is compared to these zones. In addition to a caution zone based on the weighted rms acceleration (second power), a caution zone is also provided on the basis of weighted fourth power vibration dose method. The vibration dose value (VDV) represents a cumulative exposure and is more sensitive to peaks in the exposure. It is noted that the emphasis of these standards is on the health risk to the lumbar spine.

The ISO 2631-1: 1997 also provides likely comfort reactions to vibration occurring in public transport. For assessing comfort, the acceleration is measured in each translational axis at the main supporting surfaces (seat pan, seatback, and feet). For vibration occurring in more than one direction, the point vibration total value is calculated at each surface or location using the root-sum-of-squares of the weighted accelerations. If the comfort is affected by vibration at several locations (i.e., seat pan, seatback, or feet), the overall vibration total value is calculated from the root-sum-of-squares of the respective point vibration total values. In addition, the ISO 2631-1: 1997 includes guidelines for the effects of vibration on the incidence of motion sickness in the frequency range from 0.1 to 0.5 Hz. The ISO 2631-1: 1997 has been recently applied to assess and compare the vibration occurring in selected military propeller aircraft (25).

Part 5 of the ISO 2631 titled "Method for the Evaluation of Vibration Containing Multiple Shocks (ISO 2631-5: 2004)" was developed to assess the effects of repeated shocks on the health of the lumbar spine. Exposures to multiple shocks may occur in the operation of aircraft in rough air, vehicles driving over rough terrain, or boats traveling in rough seas. An acceleration dose is calculated using a

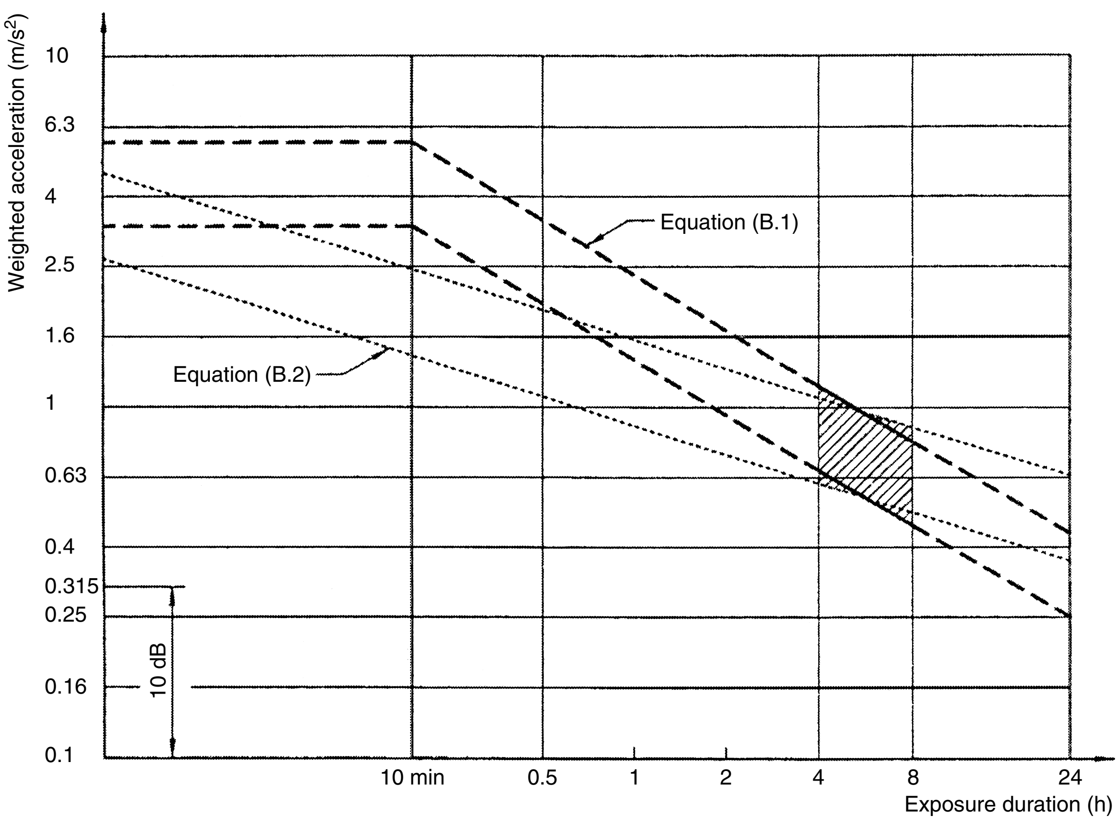


FIGURE 5-8 ISO 2631-1: 1997(E) Health Guidance Caution Zones. Equation (B.1) is defined by the following relationship: $a_{w1} \cdot T_1^{1/2} = a_{w2} \cdot T_2^{1/2}$. Equation (B.2) is defined by the following relationship: $a_{w1} \cdot T_1^{1/4} = a_{w2} \cdot T_2^{1/4}$. International Standards Organization (ISO). *Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements*. ISO 2631-1:1997(E), 1997. [© ISO. This material is reproduced from ISO 2631-1 with permission of the American National Standards Institute (ANSI) on behalf of the International Organization for Standardization (ISO). No part of this material may be copied or reproduced in any form, electronic retrieval system or otherwise or made available on the Internet, a public network, by satellite or otherwise without the prior written consent of the ANSI. Copies of this standard may be purchased from the ANSI, 25 West 43rd Street, New York, NY 10036, (212) 642-4900, http://webstore.ansi.org.]

biomechanical model and the measurements defined in ISO 2631-1: 1997 for the seat pan. The model predicts the response of the lumbar spine to a given input. The standard provides guidelines on the probability of an adverse health effect based on the acceleration dose, the ultimate strength of the lumbar spine, the person's age, and number of years of exposures.

European Union Directive

The European Union established its human vibration directive in 2002 (Directive 2002/44/EC) (26). The directive uses the ISO guidelines for measuring the vibration exposure in each translational axis. The directive defines an exposure action value (EAV) and exposure limit value (ELV) based on either the 8-hour energy-equivalent frequency-weighted acceleration level (A8 in ISO 2631-1: 1997) or the VDV (ISO 2631-1: 1997). If the EAV is exceeded, the employer must take appropriate action to try and reduce the daily exposure. If the ELV is exceeded, the health risk is considered to be high enough to prohibit further exposure.

United States Government Standards

There are specifications and guidelines given for vibration exposure in military operations including the Department of Defense Design Criteria Standard, Human Engineering, MIL-STD-1472E (27). Other government standards include the Man-Systems Integration Standards, NASA-STD-3000 (28) and the American Conference of Governmental Industrial Hygienist (ACGIH), Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs) (29). Only the MIL-STD-1472E refers to the 1997 ISO 2631-1 guidelines. As of 2006, the NASA-STD-3000 is based on previous editions of the ISO 2631-1. The ACGIH provides TLVs based on the weighted rms acceleration curves given in ISO 2631/1-1985 that are both time and frequency dependent. These values refer to that limit under which most workers may be repeatedly exposed with minimum risk to health (particularly with reference to back problems) with an emphasis on ground vehicles and heavy equipment.

Current airborne vibration exposure criteria (as of 2006) are given with respect to the noise level. The Air Force Occupational Safety, and Health Standard, AFOSHSTD 48-20 (30) recommends that, for minimizing whole body vibration effects, no octave or one-third octave band noise level exceeds 145 dB for frequencies in the range of 1 to 40,000 Hz, and that the overall sound pressure level (OASPL) be below 150 dB (unweighted). There are no time limits for exposures below these levels.

Vibration Mitigation Strategies

One obvious solution for reducing aerospace vibration is to eliminate the vibration at the source. The other approach is to isolate the occupant and equipment from the source of vibration. Eliminating the source of vibration may be quite difficult (as well as costly), particularly if the source may be an unavoidable consequence of the vehicle interaction with the operational environment (turbulence and vehicle resonance). In the case of propeller-driven or rotary-winged vehicles, vibration may be mitigated to acceptable levels by insuring proper propeller balance and synchronization (25). As mentioned at the beginning of the chapter, the rotor speed and number of blades also play an important role in defining the vibration characteristics of an aircraft. For the propeller-driven aircraft, it may be possible to isolate the occupant and equipment by relocating them to areas where the vibration is expected to be lower depending on the aircraft (away from the propeller plane). Currently available vibration damping and isolation techniques may be used to minimize vibration at higher frequencies, but designing such processes and mechanisms to reduce low-frequency vibration for which humans are the most sensitive is still a challenge. However, developing seat cushions that distribute seated pressure may help reduce the discomfort in localized regions of high loading. The discomfort, fatigue, and potential visual effects of higher frequency vibration should not be neglected. Damping and isolation of controls, displays, and seating systems may mitigate some of these effects. In the case of HMDs and targeting systems, physically minimizing the involuntary head motion associated with low-frequency vibration is also a challenge. Computer software and active feedback mechanisms may be used to reduce the adverse effects on performance. In some cases, rigid coupling between the body and contact surfaces may minimize unstable motion at very low frequencies that could cause repeated impact and injury. It may be more advantageous, with increasing frequency, to remove any coupling between the body and the vibration surface, such as removing the head from contact with the headrest. The development of successful mitigation processes and mechanisms for minimizing aerospace vibration requires the active participation of vehicle developers, users, equipment designers, structures experts, and human vibration experts. In addition, controlled laboratory testing and robust models can serve as tools for investigating specific vibration effects and causal factors necessary for reducing the adverse effects of aerospace vibration.

ACOUSTICS IN AEROSPACE ENVIRONMENTS

General Acoustics Terminology

Acoustics

Acoustics is the scientific study of sound including the generation, propagation, and the effects of sound waves.

Sound

Sound is the auditory sensation evoked by an oscillation in pressure, stress, particle displacement, particle velocity, and so on, in a medium with internal forces, or the superposition of such propagated oscillations.

Noise

Noise is any undesired sound. Therefore, the labeling of a particular sound is subjective, as noise has to do with an individual's perception. What is music to some listeners is noise to others. Further, a person's response to sound also has to do with their perception of the sound.

Sound Pressure Level

The sound perceived by the human ear is commonly measured as a sound pressure. The technical definition of sound pressure is the total pressure at a point minus the static pressure at that point. The unit of sound pressure is Pascal (Pa). The sound pressure level (SPL) is defined as 20 times the logarithm to the base ten of the ratio between the rms sound pressure, p, in a stated frequency band, and the reference sound pressure, p_0, of 20 μPa (31). The unit of SPL is the decibel (dB) and the symbol is L_p.

$$L_p = 20 \log_{10}(p/p_0) \quad [5]$$

SPLs can be logarithmically added across frequency bands to calculate an OASPL. Sound levels are the SPLs adjusted by a weighting to better represent the varying sensitivity of the human ear to different frequencies and sound pressure ranges. The A-weighting was introduced for levels below approximately 55 dB, B-weighting was for levels between 55 dB and 85 dB, and C-weighting was designed for levels above 85 dB (32). A-weighting is almost exclusively used for measurements relating to the human response to noise for both hearing damage and annoyance. The difference between A-weighted and C-weighted sound levels is an indication of the low-frequency energy content in a sound spectrum. The A-weighted sound level is denoted by L_A and expressed in dBA units.

Sound Power Level

The definition of sound power is the sound energy radiated by a source per unit time. The unit of sound power is watt (W). The human ear does not perceive sound power, only sound pressure. The sound power level (PWL) is ten times the logarithm to the base ten of the ratio of a given sound power, W, in a stated frequency band to the reference power, W_0, of 1 picowatt (1 pW) (31). The unit of PWL is the dB and the symbol is L_W.

$$L_W = 10 \log_{10}(W/W_0) \quad [6]$$

PWLs can be logarithmically added across audio frequency bands to calculate an overall PWL. Summation of all the PWL for all noise sources inside is a key factor in a number of analyses. Although PWLs and SPLs are both reported in dB, the two levels are not interchangeable. Sound power is the total acoustic energy being radiated by a source in all directions. If the sound power of a source is known and the acoustic characteristics of a room or other enclosure are known, the SPL can be calculated for a crewmember's location.

Spectrum

The spectrum of sound represents the sound pressure or power distributed across frequency. It is commonly described in terms of levels in successive pass bands of octave, half-octave, and third-octave bandwidths but can be in a successive bandwidth of any size. Noises of concern to aerospace medicine are frequency dependent in terms of their effects on humans. The spectrum of acoustic energy important to human perception ranges from less than 1 Hz to more than 20 kHz. The young, normal human ear is sensitive to acoustic energy of approximately 15 Hz to 20 kHz, which is termed the *audio frequency range*. Infrasound, energy below approximately 20 Hz, can be perceived at high-intensity levels but not as pure tones. Ultrasound is classically defined as acoustic energy above 20 kHz; however, the term is applied to energy as low as 8 to 10 kHz, and subharmonics of ultrasonic levels above 20 kHz can affect SPLs in the hearing range.

Time History

Pressure time histories describe variations in the sound pressure of an acoustic event as a function of time. The frequency content is not quantified in pressure time histories of signals. However, high-speed spectrum analyzers will give a three-dimensional (3-D) depiction of sound pressure versus frequency band as a function of time. Steady state sounds are those with a time course or duration greater than 1 second. Measurements in aerospace vehicles are usually taken over a time period of 15 seconds. Impulse sounds, individual pressure pulses of sudden onset and brief duration, are those with a time interval of less than 1 second and a peak-to-rms ratio greater than 10 dB. Impulse sounds are typically described by the rise time, peak level, duration, and number of events or repetitions. The frequency content of impulse sounds is determined by spectral-energy-density analysis.

Sound Propagation in Free Field

Theoretically, sound waves in a free field (i.e., an acoustic space with no reflections) spread spherically in all directions from an idealized point source. As a result of the spherical dispersion, the sound pressure is reduced to half of its original value as the distance is doubled, which is a 6-dB reduction in SPL. The speed of sound in air is density dependent and is therefore a function of air temperature, barometric pressure, and relative humidity. However, temperature is the largest factor in the speed of sound in air, which is approximately 344 m/s (1,129 ft/s) at a temperature of 21°C. Practically, aerospace noises do not radiate uniformly in all directions, but follow forms or patterns characteristic of the source and obstructions in the pathways. This directivity of sound radiation must be included in the evaluation of noise to ensure the appropriate placement of personnel.

Sound in Enclosed Spaces

Interior aerospace environments are enclosed spaces in which sound is reflected multiple times from the boundaries. A receiver within the enclosure is exposed to sound coming directly from the source (direct field) and sound arriving after having been reflected off one or more boundaries (reverberant sound field). The direct field is only source and distance dependent and is not affected by the size of the enclosure or the reflective characteristics of the boundaries. The reverberant field is strongly dependent on the dimensions of the enclosure and the sound-absorbing properties of the bordering walls. Owing to multiple wall reflections, the magnitude of the reverberant field builds up to a level determined by the acoustic absorption of the enclosure and the surface area of the enclosure. Sound energy density in an enclosure, of which the largest dimension is not more than three times any other dimension and much larger than the acoustic wavelength (high frequencies), will approach uniformity throughout the enclosure away from the sound source and the enclosure walls. As the distance from the sound source increases, the relative contribution of the reverberant field to the OASPL will increase until it dominates the direct sound field (32). The reverberant acoustic field is characterized by the reverberation time which is the time required for the energy density to be reduced to 60 dB below its steady-state value after a sound source has been stopped. The reverberation time is an important parameter to determine adequate speech communication characteristics in an interior aerospace environment. In enclosures with parallel walls, some of the acoustic waves emanating from the source will propagate along certain paths where they repeat upon themselves and form normal modes of acoustic vibration or standing waves. In the presence of lower-order standing waves, the response of the interior space is a function of frequency and location, and the spatial SPL distribution will be irregular and may vary substantially. Aerospace vehicles can produce high acoustic levels in relatively small, enclosed volumes. Acoustic environments in these vehicles need to be maintained at manageable levels so that the crew and passengers are afforded a safe, functional, effective, and comfortable environment.

Multiple Sound Sources

Two coherent (fixed relative phase) tonal sounds at the same frequency add vectorially and their relative phase will determine their sum to be somewhere between 3 dB and 6 dB. Practically, most sounds emanating from two sources are incoherent and are summed (in an acoustic free field) on a pressure squared, or linear energy basis, resulting in a 3 dB increase in SPL. In settings where a reflector, such as the ground or a wall, is near the source, the summation would be more than 3 dB as a result of the reflected energy. Many sources such as jet engines have both constructive and destructive frequency-dependent interference and in those cases, the addition of a second source may result in an increase of SPL from 2 to 5 dB in practice.

Aerospace Noise Environments

Atmospheric Flight

Aerodynamic noise generated by a vehicle moving through the atmosphere is a significant source during atmospheric flight. For powered aircraft, the propulsion system required to power the aerospace vehicle through the earth atmosphere is usually the most intense source. The specific noise environments for several vehicles are discussed in the subsequent text.

Gliders

The noise associated with gliders such as sailplanes, hang gliders, and paragliders is the aerodynamic noise generated from the object and pilot moving through the air. The noise is mainly dependent on the aerodynamic design of the glider, including the pilot, the speed relative to the air medium and the turbulence in the air. Helmets are mandatory for hang glider and paraglider pilots and help reduce the aerodynamic noise arriving at the pilot's ears. When flying in tandem, shouting (or the use of an electronic communication system) is needed to achieve effective communication.

Ultralights

Lightweight and slow-flying aircraft, including powered hang gliders (trikes), powered paragliders, and rotary wing craft, are often referred to as *ultralights* or *recreational aircraft*. The vehicles are often an open-air design with the pilot (and passenger) located very close to the engine and propeller or rotor. The engines are typically two-stroke or four-stroke piston engines driving high-rotational-speed propellers. The proximity of the propeller and engine sound sources to the pilot and passenger(s) presents a real concern for the well-being of their hearing. Studies have shown that pusher propeller–driven ultralight planes were 5 to 15 dB noisier than those equipped with tractor propellers (33). Acoustically well-designed helmets (possibly with active noise control), muffled engines, and low blade tip speed propellers help minimize the noise hazard.

Propeller Aircraft

Loud tonal noise from piston or turbo propeller engines in the cabins of some general aviation, commercial and military aircraft may pose a threat to the hearing and comfort of the occupants and the effectiveness of voice communications. Beating noise occurs when the tonal noises from two propellers are at similar levels but differ slightly in frequency. Synchronization of the propellers may cease this modulation. Consistent use of appropriate personal noise-excluding equipment can greatly reduce or eliminate the threat of potential noise-induced hearing loss (NIHL) and deteriorated audio communications.

Rotorcraft

Significant rotorcraft cabin noise sources include the impulsive, periodic, and broadband noises from the rotors and the structure-borne noises from, especially, the gearbox. Present communication equipment in helicopters may become marginal or inadequate for some phases of flight. Aircrew members may be vulnerable when required to work in maximum level noise areas inside open or closed helicopters. Medical rescue and other personnel immediately outside the helicopter in the direct downwash of the rotating blades may find both the transmission and reception of voice communication marginal to unacceptable. Helicopter noise spectra contain high-level, low-frequency noise for which sound attenuating properties of flight helmets and headsets are least effective. Substantial progress has been made in the development of special noise-excluding headwear, and some helicopter noise situations will benefit from these developments.

Jet-Powered Aircraft

Aerodynamically induced energy is at a maximum for aircraft during liftoff, climb out, dives, supersonic dashes, and maneuvers. This category of acoustic energy is of relatively high frequency, which is more easily controlled than the low-frequency content. Airborne and structure-borne noise from the engines, the turbulent boundary layer over the fuselage and airframe noise all contribute to the interior acoustic environment. The character and the level of the noise vary with aircraft type, flight operation, and flight condition. Interior noise levels may be considerably higher for full-power engine operation during takeoff and the reverse thrust operation during landing. However, these conditions are experienced for only short durations compared to the duration of the cruise flight. High interior noise levels on long flights may cause discomfort, fatigue, annoyance, sleeplessness, and irritation. Under those circumstances, occupants may want to use earplugs or noise-canceling headphones to alleviate detrimental effects. The flight crew compartments of most commercial passenger aircraft are sufficiently sound treated to minimize or eliminate noise as a voice communication problem. It is desirable that ambient noise levels in commercial aircraft passenger compartments are high enough to provide acoustic privacy for the conversations of passengers seated close to one another. Conversations from nearby passengers, not masked by the background noise, may cause speech interference and feelings of discontent with the acoustic environment.

Fighter Aircraft

In most fighter aircraft now flown, acoustic levels are typically approximately 105 dB, but levels can go down to 95 dB during descent or other flight operations, and at the worst, can reach levels between 115 and 118 dB (Teleconference between Goodman JR, McKinley RM. Wright-Patterson AFB, Ohio: February, 2007;16.). High performance aircraft require voice communication equipment to be integrated with the flight helmet–oxygen mask system. Typically, this consists of high-quality, altitude-compensated earphones inside the helmet and a noise-canceling microphone in the oxygen mask. Both the helmet and oxygen mask act as noise shields. Crewmembers of other types of military aircraft may use the flight helmet with a noise-canceling microphone mounted on a boom or simply a headset that also includes a noise-canceling boom microphone, or in some cases, dual hearing protection is required. These terminal equipment items are designed specifically for the noise environments in which they are used and their performance is reliable.

Launch Vehicles During Liftoff

The intense combustion and powerful thrust required to propel a space vehicle during liftoff generates noise that is transmitted throughout the vehicle structure and internally to the crew stations. These high-level noises are typically of short duration. The OASPL for the Space Shuttle during launch measured approximately 149 dB externally and 118 dB internally. Adequate hearing protection is required during this portion of the flight to prevent damaging effects to the hearing of the crew.

Space Flight

Noises during space flight originate in the space vehicle itself. The acoustic environment is characterized by the type of the noise sources, the kind of operations, the number, layout, and levels of the noise sources, the design of the source enclosures, the geometry and acoustic properties of the crew habitable volume, and environmental factors.

Space Shuttle Orbiter

The Space Shuttle Orbiter (Orbiter) was originally designed to be operated for 10 to 14 days, but was later modified for extended-duration operations of up to 16 days plus 2 contingency days. The predominant noise sources in the Orbiter are the cabin fans and other noise sources include avionics, cooling fans, water pumps, and water separator. Payloads manifested onboard introduce additional continuous or intermittent noise sources. Levels normally range from 65 dBA to 68 dBA when payloads are flown and used. During the STS-40 mission, noise levels exceeded the specification levels in both the Orbiter and Spacelab. The Spacelab levels went up to a time-weighted average (TWA) as high as approximately 76 dBA due to experiments and exercise noise, and created significant concerns: inadequate communications, annoyance, poor habitability, and hearing threshold shifts. This situation was created by inadequately controlling the mix of payloads and their operations.

International Space Station

The International Space Station (ISS) is an on-orbit laboratory workshop and a home with long-term crew occupation. Mission duration for the crews in ISS may range from 3 months to 7 or more months at present. ISS modules have equipment such as fans, pumps, compressors, avionics, and other noise-producing hardware and systems to serve their functional, life-support, and thermal control needs. Payload racks with scientific operating equipment create continuous or intermittent noises or combinations of both. The crew exercises on a treadmill and uses other conditioning devices, which all generate noise. In the ISS, payload racks can be added or changed during a mission. Communications between the crew and the ground are at raised levels to communicate over the background environment, adding to the overall crew noise exposure. Acoustic levels at most locations in the ISS are close to 60 dBA (34). The Service Module (SM) which is the activity center due to eating, hygiene, and communication activities, has elevated noise levels. This module has required the use of hearing protection devices over long periods of time. SM upgrades that were implemented since 2003 have lowered the sound levels and more improvements in the acoustic environment are planned.

Exploration Mission Vehicles

Initial exploration missions to the moon are planned for up to 14 days. Acoustic management challenges are significantly increased as the travel time for future spacecraft to destinations beyond the moon is measured in years rather than months and the available physical living and working environments are smaller than the ISS interior space. Manned outposts planned for the moon and Mars will also be an acoustics challenge. Acoustic requirements for such missions will have to be adjusted to better consider the effects of long-term exposures, communications, and habitability. These missions will be more autonomous and crews will not have normal responses from mission control nor the relief offered by a relatively quick return home from orbit.

Noise and Speech Analysis

Noise Exposure Metrics

Noise exposure metrics have been established to quantify the human exposure to sound. Following are the definitions of some noise exposure metrics applicable to the aerospace noise environments.

Time-Weighted Average

An individual's noise exposure typically varies by level and duration during a work period. These variations in noise exposure are combined to define the person's time-weighted average (TWA). The TWA is expressed in dBA and is calculated using the noise exposure criterion specified in an adopted hearing conservation program. Acoustic energy is doubled if it is increased by 3 dB, and halved when decreased by 3 dB. Variations in the exposure time correspond to this pattern. The following equation defines the TWA as follows:

$$TWA = 10\log\left[\frac{1}{480}\sum_{i=1}^{n}\left(2^{(L_{Ai}-85)/3}t_i\right)\right] + 85 \qquad [7]$$

where i is the individual exposure interval, n is the total number of exposure intervals in the day, t is the exposure time in minutes for exposure interval i, and L_{Ai} is the A-weighted SPL (dBA) at the ears for the exposure interval. The TWA can be calculated for any number of exposure intervals, each having its own exposure level.

Equivalent Sound Level (L_{eq})

The equivalent sound level (L_{eq}) is the A-weighted SPL of a fluctuating sound averaged over a given time interval. The time interval over which the levels are averaged is typically defined as 1 minute, 1 hour, 8 hours, or 24 hours depending upon the importance of the time interval and application. The L_{eq} is defined by the following equation and has units of dBA

$$L_{eq} = 10\log\left[1/T\sum_{i=1}^{n}10^{L_{Ai}/10}t_i\right] \qquad [8]$$

where i is the individual exposure interval, n is the total number of exposure intervals, t_i is the duration in minutes for interval i, T is the total time in minutes for the L_{eq} (such as 1, 60, 480, or 1,440), and L_{Ai} is the A-weighted SPL (dBA) for interval i. Time-varying sound can also be expressed by a sound level indicating the percentage of time a level is exceeded. As an example, the sound level L_{10} indicates that the level is exceeded 10% of the time and identifies the high level components of a sound. L_{90} is a measure of the ambient or residual level.

Speech Intelligibility Descriptors

The most pervasive operational threat to voice communications is noise. Speech communication assessment techniques use physical measurements that compare the noise signal to the speech signal to evaluate the masking effect on the speech. These techniques range from the simplest (A-weighted sound level) to the most complex method (speech intelligibility index or SII) for determining the intelligibility of speech under a variety of situations. The most accurate procedure measures the intelligibility response with operators using the communications equipment of interest in the actual or accurately emulated acoustic environment of interest.

A-Weighted Sound Level

A-weighted sound level values are used to display the quality of various types of communication as a function of the sound level of the noise. Examples for face-to-face, intercom, and public address system communications in a range of A-weighted sound level background noises are shown in

TABLE 5-1

Speech Communication Capabilities versus A-Weighted Sound Pressure Level (dBA) Background Noise

Communication	*Below 50 dBA*	*50–70 dBA*	*70–90 dBA*	*90–100 dBA*	*110–130 dBA*
Face-to-face (unamplified speech)	Normal voice at distances up to 6 m	Raised voice at distances up to 2 m	Very loud or shouted voice level at distances up to 50 cm	Maximum voice level at distances up to 25 cm	Very difficult; impossible even at a distance of 1 cm
Intercom system	Good	Satisfactory to difficult	Unsatisfactory using loudspeaker	Impossible using loudspeaker	Impossible using loudspeaker
Public address system	Good	Satisfactory	Satisfactory to difficult	Difficult	Very difficult

Table 5-1. The A-weighted sound level procedure is suitable for prediction of intelligibility for purposes such as surveying and monitoring. It is less practical for noise control and engineering purposes because noise spectral information is lacking.

Speech Interference Level

Speech interference level (SIL) is an indicator used to evaluate the effect of steady background levels on the quality of face-to-face speech communication. The SIL is the arithmetic average of the SPL of the interfering noise in the four octave bands centered at 500, 1,000, 2,000, and 4,000 Hz. The U.S. Federal Aviation Administration (FAA) uses the more recent Preferred Speech Interference Level (PSIL) that only includes the 500, 1,000, and 2,000 Hz octave bands. The quality of communications expected for PSIL and dBA values at several separation distances and voice levels are shown in Figure 5-9. The accuracy of the PSIL decreases in reverberant spaces.

Noise Criteria

Noise criteria (NC) ratings are used to determine quality of speech communication based on the octave band levels of the noise in the environment of interest. To evaluate a space, the measured octave band levels of the noise are converted to an NC rating. Descriptions are provided of the living conditions that correspond to the derived NC values. The curves associated with the NC ratings are presented in Reference (32). NC curves have been used for initial requirements in the Orbiter, are implemented as requirements in ISS, and planned to be used in the Constellation Program for exploration missions. These NC curves as the continuous noise limits for space vehicles are discussed in more detail in the section **Noise Regulations, Measurements, and Control**.

Balanced Noise Criteria

Balanced noise criteria (NCB), an expansion of NC criteria, provide guidance for the specification or the assessment and control of noise environments. It is used to enable satisfactory speech communication and habitation in indoor spaces by considering disturbances and annoyance resulting from sound and vibration. SIL is used by NCB to determine the acceptability of speech communication in an environment of interest. NCB curves and NCB values for various types of workspaces and comprehensive guidance on their use can be found in Reference (35). Procedures for determination of the presence of rumble and hiss in an environment are also included in the NCB (35).

Speech Intelligibility Index

The calculation of the articulation index (AI) has been used for several decades as a measure of the intelligibility of voice signals, expressed as a percentage of speech units that are understood by the listener when heard out of context (36). The SII (37) is a major revision of the AI standard and defines computational methods that produce results highly correlated with the intelligibility of speech under a variety of adverse listening conditions, such as noise masking, filtering, and reverberation. The SII is computed from acoustic measurements or estimates of the speech spectrum level, the noise spectrum level, and from physical psychoacoustical measurements of the hearing threshold

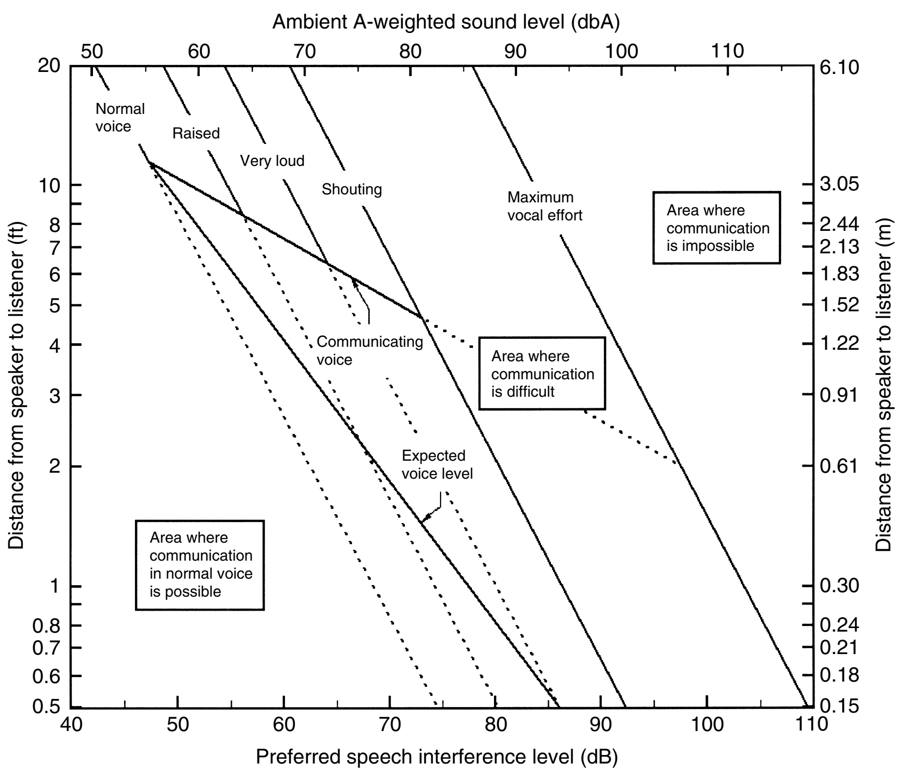


FIGURE 5-9 Effectiveness of voice communications as a function of preferred speech interference level (PSIL) and distance from speaker to listener.

level. Various audio frequencies contribute different amounts to speech intelligibility, and, within a certain range, a higher speech-to-noise ratio means higher intelligibility. The intelligibility of a speech communication system is predicted by measuring the speech-to-noise ratio in each contributing band and adding the results. The computed SII is converted to speech intelligibility scores.

Speech Transmission Index

The Speech Transmission Index (STI), like SII, is based on the AI. Speech intelligibility based on measurements of the communication system or on calculations is objectively predicted by the STI, provided all necessary information is available. It yields a single-number index of 0 to 1 that correlates well with other psychophysical measures of speech intelligibility. An STI value of 0.6 is required for a communication with a minimal rating of "good." A value of 0.35 corresponds with approximately 50% intelligibility of redundant sentences. The STI can also be used with digital communication systems (38,39).

Speech Intelligibility Tests

Standardized methodologies are used to measure the performance of occupied habitable volumes, total voice communication systems, and the individual components of the communication chain with or without the person-in-the-loop. These methods are based on the subjective assessment of speech intelligibility. The basic unit is the percentage of a given sample of speech correctly perceived by an observer. These samples comprise groups of syllables, words, phrases, and/or sentences that are directly related to everyday speech. Most of these materials, or intelligibility tests, were standardized with human operators-in-the-loop and they provide reliable measurements that can be generalized to other populations. Three procedures used in speech intelligibility testing have been standardized and are described in ANSI S3.2–1989 (40). They include the Phonetically Balanced (PB) Monosyllabic Word Intelligibility Test, Modified Rhyme Test (MRT), and the Diagnostic Rhyme Test (DRT).

Effects of Noise on Crew and Crew Communications

The effects of aerospace noises on humans have been divided into physiological and psychological responses. Physiological responses, both auditory and nonauditory, involve changes in physiological mechanisms or functions attributed to the noise. Auditory effects are confined to direct influences on the peripheral auditory system and the hearing function. Acoustic energy exposures can also affect the vestibular system, the autonomic nervous system, sleep, produce startle, and can induce fatigue; however, with few exceptions, these nonauditory effects are also mediated through the auditory system. Psychological response behavior to noise is influenced by the human's perceptions, judgments, attitudes, and opinions, which may be either related or unrelated to the noise itself. Most noise exposures stimulate elements of both types of responses, which clearly interact with one another.

Audio communications in an aerospace environment are also affected by noise, possibly endangering the safety, performance, and well-being of the participants, diminishing the effectiveness and efficiency of the communications and perhaps preventing messages or (alarm) signals from being heard correctly, or received altogether.

Auditory Physiological Effects

Human Hearing Function

The human auditory system is an extremely sensitive and highly specialized mechanism that is quite adaptable and quite resistant to the adverse effects of acoustic energy unless abused (Figure 5-10) (41). The audible frequency range in the healthy, young human ear extends from approximately 15 Hz to 20 kHz. The most sensitive region of hearing is from approximately 500 Hz to 4 kHz and is most important for understanding speech. Hearing sensitivity is expressed in decibels relative to the normal threshold of hearing or standard hearing reference zero. The human usually does not notice acoustic intensity increases less than 3 dB above the initial level (at twice the energy as the original source) and psychophysically judges a sound to be about "twice as loud" when the intensity is increased by 10 dB. Signal

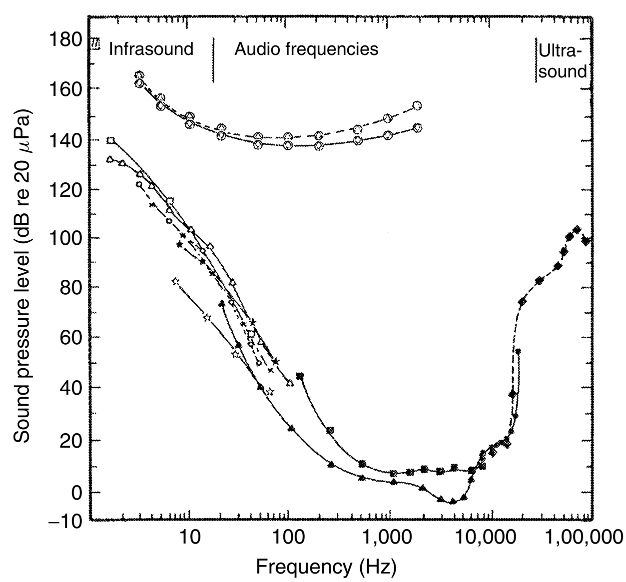


FIGURE 5-10 Human auditory sensitivity and pain threshold levels. □ = Von Bekesy (1960) Data-Minimum Audible Pressure (MAP); ◯ = Yeowart, Bryan, and Tempest (1969) Data-MAP; △= Whittle, Collins, and Robinson (1972) Data-MAP; × = Yeowart, Bryan, and Tempest (1969) Data-MAO for bands of noise; | = Standard reference threshold values-MAP (American National Standard on Specifications for Audiometers, 1969); ▲ = ISO R226-Minimum Audible Field (1961); • = Northern, et al. (1972) Data; ⧫ = Corso (1963) Data-Bone conduction minus 40 dB; ◇ = Von Bekesy (1960) Data = Tickle, pain; △ = Benox; □ = Static Pressure-Pain; ⋆ = Yamada et al. (1986) Average hearing threshold; ★ = Yamada et al. (1986) Minimum hearing threshold. (Adapted from Nixon CW. Excessive noise exposure. In: Singh S, ed. Measurement procedures in speech, hearing, and language. Baltimore: University Park Press, 1975.)

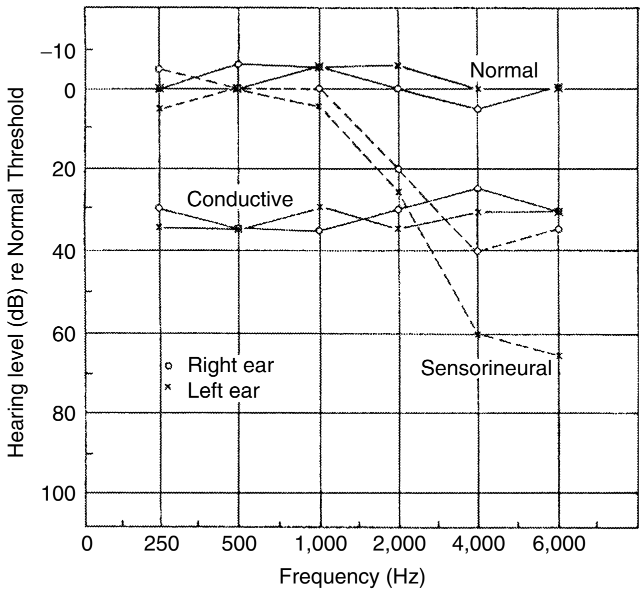


FIGURE 5-11 Typical audiograms showing normal hearing, a conductive-type hearing loss that is relatively flat, and a sensorineural or perceptive hearing loss with the characteristic loss of sensitivity with increasing frequency.

detection by the human ear requires higher SPLs in the infrasound region (below 20 Hz), and tonal quality is lost below approximately 15 Hz. Ultrasound acoustic energy (above 20 kHz) is not ordinarily perceived by the human ear. The harmonics of infrasound and subharmonics of ultrasound may be significant and perceived outside of their respective frequency regions.

An individual's hearing sensitivity for standard audiometric test frequencies is expressed in decibels hearing level (dB HL), or dBs relative to reference values of normal hearing. The range of normal hearing sensitivity for pure-tones (as measured in air-conduction audiometry) is from −10 to 25 dB HL, as shown in Figure 5-11. Hearing levels greater than 25 dB HL are considered abnormal and constitute hearing loss. Conductive type hearing losses, caused by impairment of outer and middle ear functions, usually reduce hearing sensitivity for low-frequency stimuli, or when more severe may show a flat audiogram.

Sensorineural hearing loss, usually attributed to inner ear impairment, characteristically displays a loss of sensitivity in the high frequencies. Noise-related hearing losses often appear as an audiometric "notch" pattern, in the 4 kHz or 6 kHz region, that advances (with more noise damage) into lower frequencies. The progression of noise-induced sensorineural loss correlated with the number of years of exposure has been widely documented (42). The term *mixed hearing loss* is used to define a loss with both conductive and sensorineural components.

Persons with hearing losses greater than 35 to 40 dB in the speech-frequency range (500 Hz to 4 kHz) experience communication problems and are potential candidates for hearing aid amplification, if medical remediation is not possible. Although many conductive hearing losses are often amenable to medical or surgical treatment, sensorineural hearing losses usually do not respond to such means. Consequently, prevention of such sensorineural disorders, through hearing loss prevention programs, is critically important.

A number of protective actions operate in the region of the middle ear to reduce the amount of acoustic energy transmitted to the inner ear. At high sound intensities, the motion of the stapes changes from a piston-like to a rocking action in the oval window resulting from temporary dislocation of the ossicular joints, reducing the efficiency of transmission. In addition, extremely loud sounds can trigger the acoustic reflex, which causes the stapedial and tensor tympanic muscles to contract, increasing the stiffness of the ossicular chain, and dampening the transmission of low-frequency acoustic energy. This mechanism provides no protection, however, for brief impulses (like rifle shots) shorter than 20 milliseconds owing to the slow response latency of this reflex (from 25 to 100 milliseconds).

A National Aeronautics and Space Administration (NASA) summary of physiological effects of noise is provided in Table 5-2 (43), listing various conditions of exposure in terms of SPL, frequency band, and duration for a number of reported disturbances. Other observed nonauditory physiological effects due to noise exposure are presented in Reference (43) and include the following:

- Increases in the concentration of corticosteroids in the blood and brain and change in the size of the adrenal cortex
- Electrolytic imbalances and changes in blood glucose level
- The possibility of effects on sex-hormone secretion and thyroid activity
- Reports of vasoconstriction, fluctuations in blood pressure, and cardiac muscle changes
- Abnormal heart rhythms

Static Air Pressure

Differential pressures may occur across the tympanic membrane with variations in pressure associated with changing atmospheric (flight) conditions and a Eustachian tube that remains closed. Although a high-pressure differential may cause noticeable discomfort or pain, lower pressure differences could cause an undetected decrease in hearing sensitivity of 8 dB to 10 dB for frequencies below 1,500 Hz and above 2,300 Hz. These effects are usually transitory and may be relieved by the Valsalva maneuver or other means of equalizing ambient and middle ear pressures.

Hearing Threshold Shift

NIHL may be either temporary or permanent and either type of NIHL may have significant impact on operational success. Temporary threshold shift (TTS) is a short-term loss of hearing sensitivity after exposure to noise, subject to the intensity, spectral content, and duration of the noise exposure. Although the fastest recovery of hearing typically occurs within the first 12 to 14 hours of a noise exposure,

TABLE 5-2

Physiological Effects of Noise

	Condition of Exposure		
Reported Disturbances	*Sound Pressure Level (dB) Re: 20 μPa*	*Spectrum*	*Duration*
Reduced visual acuity, chest wall vibrations, gag sensations, respiratory rhythm changes	150	1–100 Hz	2 min
Reflex response of tensing, grimacing, covering the ears, and urge to avoid or escape	100	—	Sudden onset
Pain in the ears	135	20–2,000 Hz	—
Pain in the ears	160	3 Hz	—
Discomfort in the ear	120	300–9,600 Hz	2 s
Hearing temporary threshold shift of 10 dB	94	4,000 Hz	15 min
Hearing temporary threshold shift of 10 dB	100	4,000 Hz	7 min
Hearing temporary threshold shift of 10 dB	106	4,000 Hz	4 min
Tympanic membrane rupture	155	2,000 Hz low frequency	Continuous blast
Tympanic membrane rupture	175	—	—
Mechanical vibrations of body felt, during sensations	120–150	OASPL	—
Vertigo and, occasionally, disorientation, nausea, and vomiting	120–150	1.6 To 4.4 Hz	Continuous
Irritability and fatigue	120	OASPL	—
Temporary threshold shift occurs	65	Broadband	60 d
Human lethality	167	2,000 Hz	—
Human lethality	161	2,000 Hz	—
Temporary threshold shift occurs	75	8 to 16 kHz	5 min
Temporary threshold shift occurs	110	20 to 31.5 kHz	45 min

OASPL, overall sound pressure level.

additional (although slower) recovery can continue over the next 24 to 48 hours. Intense noise exposures (e.g., from high-level impulses) or long-duration exposures to continuous noise can result in larger amounts of TTS. Individual ears vary greatly in their susceptibility to the adverse effects of noise (44). There is no evidence that hearing loss related to a given noise exposure will develop several months or years after the cessation of that noise exposure. Although the ability to determine the noise susceptibility of an ear would be most valuable before a work assignment in noise, no satisfactory method for quantifying susceptibility has been developed. Exposure standards and criteria do not include a susceptibility factor because of this wide variance and the inability to predict TTS for a specific ear. TTS can also be caused by other means such as the excessive use of aspirin or other drugs. TTS during flight is a concern because of hearing loss and operational considerations.

Permanent threshold shift (PTS) is a loss of hearing that persists, with no recovery of sensitivity, regardless of the time away from the noise. Both the TTS and the PTS types of hearing loss are measured and reported in decibels. Relationships have been established between recent TTS and noise exposure and between PTS and noise exposure experienced in daily activities performed over many years. Noise-induced TTS is considered an essential precursor to noise-induced PTS. It is further assumed that noise exposures that do not produce TTS will not produce PTS. PTS develops similarly to TTS but on a slower time scale and different noise exposures that produce equal amounts of TTS are also considered equally noxious with regard to PTS. If a residual hearing loss from TTS remains, 30 days or more postexposure, the NIHL may be considered a PTS. These assumptions, based on TTS data from the laboratory and TTS/PTS data from actual field noise exposures, have provided a basis for formulating noise exposure standards and hearing damage risk criteria (DRC) that relate noise exposure with hearing loss (45,46). Noise exposures equal to or greater than a TWA of 85 dBA for an 8-hour period are considered hazardous and can cause PTS. The development and statistical distribution of NIHL in a population as a function of daily noise exposure for exposure times from 10 years to 40 years (as well as aging) can be estimated by standardized procedures (46). However, these estimates still show wide variability in hearing threshold shifts among individuals, suggesting that other endogenous factors (e.g., gender, race, exposure to ototoxic drugs and chemicals) can influence one's own personal susceptibility to hearing loss.

The most common metric used to identify early signs of NIHL among noise-exposed personnel in hearing conservation programs is the standard (or significant) threshold shift (STS). Federal hearing standards (used by Occupational Health and Safety Administration (OSHA), the U.S. Department of Defense and NASA) define STS as an average change in hearing threshold in either ear of 10 dB or more from baseline at 2,000, 3,000, and 4,000 Hz (30,47–49), where NIHL is first evidenced. Although the STS may be computed using age corrections, described in OSHA 29 Code of Federal Regulations (CFR) 1910.95, Appendix F (47), such corrections may be eliminated to provide an earlier alert of developing NIHL.

Presbycusis

Noise-induced sensorineural hearing loss may be confounded by presbycusis (42), which is the gradual loss of high-frequency auditory sensitivity that accompanies advancing age in much of the population. Such high-frequency hearing loss due to aging often occurs, ironically, at several of the same frequencies for which NIHL occurs. Although not a standard procedure, some evaluations of NIHL attempt to estimate what portion of the loss, if any, is contributed by presbycusis. This may be accomplished statistically by subtracting the average presbycusis value for a non–noise-exposed population from the hearing loss values at each frequency. Present data suggest less presbycusis loss for women than for men, whereas there appears to be no gender differences with respect to NIHL (45). The remaining loss of hearing may be attributed to the noise exposure history of the individual, other factors considered.

Auditory Pain

Auditory pain resulting from intense noise is associated with excessive mechanical displacement of the middle ear system and is believed to occur in the threshold region at which damage begins. Noise-induced auditory pain occurs almost independent of frequency at levels of 130 dB to 140 dB SPL and above. No pain is associated with overexposure of the inner ear. However, tinnitus (ringing or similar sounds in the ear) is often a more obvious alert that noise exposures have been excessive.

NASA's standards for broadband limits in space state that crewmembers shall not be exposed to continuous noise levels that exceed 120 dB in any octave band or 135 dB OASPL under any circumstances (43). Other limits are discussed in the section **Noise Regulations**.

Nonauditory Physiological Effects

Generally, humans adapt quite well to stimuli such as noise; however, adaptation has not been demonstrated by the responses of a variety of nonauditory systems. Changes in physiological responses to noise have been measured under laboratory conditions and in real-life situations; however, the magnitudes of these changes are often no greater than those experienced under typical daily living conditions. Although some physiological reactions to certain noises occur at levels as low as 70 dBA, the state of understanding is still unclear about relationships between potential adverse physiological effects and general noise exposure, as well as to the significance to general health and well-being of the changes that do occur (42).

General Physiological Responses

Most nonauditory effects mediated through the auditory system may be avoided with the use of appropriate hearing protection. Unfortunately, use of hearing protectors may have a negative effect on communication (e.g., where the wearer has a preexisting hearing loss). Such devices may also become uncomfortable for long-term wear. Even with maximum hearing protection, exposure to SPLs in excess of 150 dB should be prohibited because of mechanical stimulation of receptors other than the ear. Noise spectra containing intense low-frequency and infrasonic energy may excite body parts such as the chest, abdomen, eyes, and sinus cavities, causing concern, annoyance, and fatigue. The response of the vestibular system to extremely high levels of noise apparently mediated through the auditory system can manifest itself by disorientation, motion sickness, and interference with postural equilibrium.

General and specific physiological responses to sound include effects on peripheral blood flow, respiration, galvanic skin response, skeletal muscle tension, gastrointestinal motility, cardiac response, pupillary dilation, headaches, and renal and glandular function. The contribution of conditions such as temperature extremes, poor ventilation, threat of accidental injury or death, special task demands, and other non–noise elements that tend to grow as noise intensity grows cannot be ascertained with current data.

Subjective reports of disorientation, vertigo, nausea, and interference with postural equilibrium during high-intensity noise exposure suggest stimulation of the vestibular system. Empirical efforts to demonstrate the vestibular response to acoustic energy have been inconclusive; however, evidence does suggest that the vestibular system is the most probable site responding to the acoustic stimulation. Other than the vestibular system, mechanoreceptors and proprioceptors may be the primary mediators of physiological responses at SPLs above 140 dB.

Sleep Interference

Sleep is a physiological necessity. Interruption and acute lack of sleep can adversely affect rest, relaxation, performance, and health. Sensitivity to noise varies among individuals in the population and with factors such as aging. Young people are the least sensitive, and older adults are the most sensitive to awakening by sounds. Familiar sounds or words may waken a person at levels much lower than those required for less familiar sounds. Sleep interference resulting from noise may arouse or waken a person. It can also induce changes in the stages of sleep of a person who does not waken. People are more susceptible to behavioral wakening during sleep stage 2 compared to other stages and are most resistant to awakening in deep sleep stage 4 and during rapid eye movements (REMs) with dreaming. People not awakened by noise stimuli have displayed changes in electroencephalographic recordings, as well as in peripheral vasoconstriction and heart rate during the sleep. People who experience these biologic changes are unaware of the acoustic exposure and the sleep stage changes. After a period of sleep deprivation almost all time is spent in sleep stages 3, 4, and REM and the sensitivity to wakening is decreased. The primary impact of sleep deprivation is fatigue. Effects of aircraft noise exposure on sleep have been studied extensively in the laboratory and the community. Noises that are adequate stimuli do cause sleep disturbances and associated annoyances. However, it is still not known if or how awakenings or sleep stage changes relate to health effects (50).

NASA's space program has encountered sleep interference concerns since the Apollo Program. Space Shuttle Orbiter missions had problems due to high noise levels from payload operations, as well as during dual shift operations on the Orbiter mid-deck, where both work and sleep were required within the same relatively small cabin volume. Sleeping bunks were added and extensive noise control measures were implemented to provide quiet rest and sleeping areas in the Orbiter and ISS.

Startle

Startle may be evoked by a wide variety of stimuli but is a particularly common response to sudden, unexpected noises. The physiological aspects of the startle response are usually independent of the stimulus and include increased pulse rate, increased blood pressure, and diversion of blood flow to the peripheral limbs and gross musculature. The universality and uniformity of this reaction from one person to another suggests that startle is an inborn reaction that is modified little by learning and experience.

Several studies point out that nonauditory physiological responses to acoustic energy have been observed and measured among selected populations. At the same time, it should be emphasized that these findings are not sufficiently clear or consistent to demonstrate relationships reliable enough to generalize about any typical populations. The aerospace physician must evaluate potential adverse effects of aerospace noise environments on an individual basis, especially when they fall outside the conditions specified in existing standards and criteria for allowable noise exposures. In ISS, noise levels from an intermittent noise source in the U.S. Laboratory were significantly high enough to create a startle concern, so design changes were made to lower the levels of the source.

Psychological Effects

Numerous psychological factors in the lives of individuals, such as their perceptions, beliefs, attitudes, and opinions, contribute to the manner in which they respond to noise from aerospace activities. These responses are generally treated in terms of annoyance, irritation, impacts to operations/performance, and speech communication, which is a special task addressed in a separate section of this chapter.

Annoyance

Acoustic energy is undesirable when it becomes a distraction or when it interferes with routine activities. Individuals become annoyed when the amount of interference becomes significant. Numerous techniques based on measurement of the physical stimulus are used to assess noise exposure effects on people in work and living spaces. One concept maintains that the human reaction to a sound is determined by the annoyance or unwantedness of the sound instead of its loudness. This subjectively judged unwantedness of sounds is described as perceived noisiness (PN). PN may be adequately determined by using the physical measurements of the sound to calculate PN in dBs, or perceived noisiness in decibels (PNdB).

A different concept of estimating annoyance incorporates both the duration and magnitude of all the acoustic energy occurring during a given time. The measurement is the L_{eq} as defined previously. The problem of quantifying environmental noise is greatly simplified using the statistical measures of the L_{eq}. The L_{eq} is one of the most important measures of environmental noise for assessing effects on humans, because experimental evidence suggests that it accurately describes the development of NIHL and that it relates to human annoyance resulting from noise.

Sleep Interference and Startle

Both sleep interference and startle have substantial psychological components in addition to the clear-cut physiological components discussed earlier. In fact, the major adverse reaction of annoyance is usually caused by being startled or awakened and not because of the changes in physiological response that occur. The personal feelings of the exposed individual regarding factors such as the reason for the disturbance, loss of control of one's environment, concern over the reason for the disturbance, concern over how to minimize and eliminate the disturbance, and other factors usually determine the degree of acceptance of or annoyance to the acoustic energy. In ISS, changes were made to lower the levels of intermittent vacuum venting of payloads because of startle concerns. Astronauts indicated that this noise source would sound just like a cabin leak.

Performance Degradation

The effects of noise on cognitive and sensorimotor performance remain unclear and very complex. The same general experimental conditions have produced performance enhancement on some occasions and performance degradation on others. However, performance degradation resulting from noise has been reported with reasonable consistency in a number of task situations. The efficiency of vigilance tasks (requiring alertness) over long periods was degraded in noise environments of approximately 100 dB. Mental counting tasks were influenced in a complex manner, and time judgments were distorted. High-frequency noise of sufficient intensity produces more harmful effects on performance than do low-frequency noises. Sudden and unexpected changes in noise level, either up or down, may produce momentary disturbances. Noise ordinarily increases the number of errors but does not reduce the speed at which work is performed. High tone levels can be irritating and wearing, if they last

TABLE 5-3

Performance Effects of Noise on Humans

	Condition of Exposure		
Performance Effects	*SPL (dB) Re: 20 μPa*	*Spectrum*	*Duration*
Reduced ability to balance on a thin rail	120	Broadband	—
Chronic fatigue	110	Machinery noise	8 hr
Reduced visual acuity, stereoscopic acuity, near-point accommodation	105	Aircraft engine noise	—
Vigilance decrement, altered thought processes, interference with mental work	90	Broadband	Continuous
Fatigue, nausea, headache	85	1/3-octave at 16 kHz	Continuous
Astronauts' degraded performance	75	Background noise in spacecraft	10–30 d
Performance degradation of multiple-choice, serial-reaction tasks	90	Broadband	—
Overloading of hearing due to loud speech	100	Speech	—
Affects person-to-person voice communication	Figure 1	—	—
Hearing temporary threshold shift at 2 min	70	4,000 Hz	—
Hearing temporary threshold shift at 2 min after exposure	155	—	8 hr 100 impulses

very long. In ISS, high noise levels have been a significant habitability concern and although their specific effects on performance have not been measured, they are recognized as a stressor that affects operations.

A NASA summary of performance effects of noise on humans for exposure conditions described by SPL, frequency spectrum, and duration is provided in Table 5-3 (43). Other observed performance effects of noise are listed in Reference (43) including the following:

- Continuous regular periodic and aperiodic noise reduces performance on a complex visual tracking task.
- Increasing noise intensity causes increased arousal and improved task performance up to the point where overarousal degrades task performance.
- Psychological effects of noise can include anxiety, learned helplessness, degraded task performance, narrowed attention, and/or other adverse after effects.

Noise Effects on Communications

Direct Voice Communications

The vocal effort and quality of face-to-face communications in background noises and at talker–listener separation distances are summarized in terms of A-weighting and PSIL in Figure 5-9. Satisfactory communication, approximately 90% to 95% correct perception of sentences, is expected with a normal voice at a distance of approximately 3 m in a noise level of 55 dBA (48 dB PSIL). Talkers must shout to be understood at the same separation distance in a noise level of approximately 74 dBA. To maintain good communication, voice level must increase from 3 dB (in lower noise levels) to 6 dB (in higher noise levels) for every increase of 10 dB in noise level. Generally, the average male voice is approximately 4 dB higher than the female voice. NASA standards for intelligibility (43) document AIs in the very good to excellent range, 0.7 to 1.0. For ISS, the minimum AI requirement is 0.75.

Normal voice conversations are not possible in most high-noise environments at distances greater than approximately 1 m. Aerospace environment noises that require an above-normal voice effort place additional stress on talkers and listeners. The amount of stress on the vocal cords is dependent on the level of vocal effort and frequency of required communications. Infrequent or occasional raised voices and shouts may be tolerated; however, sustained above-normal vocal effort should be avoided. Electronically aided communications should be used in these situations, when practical, to protect the health and well-being of personnel and to minimize errors resulting from inadequate communications. Figure 5-12 shows the AI levels plotted versus the NC curves or dBA levels, for the Orbiter and ISS communication distances from 5 to 8 ft, with the NASA minimum 0.75 AI requirement also shown (51). This figure is based on English male-to-male, face-to-face communications, not including mixed gender crews, different accents, or unusual orientation relative to each other (talking to someone who is upside down to you), which could affect normal communications.

Noise masking of speech and other audio warning signals threaten operator safety and performance. Intense noise levels at the ear may also cause aural overload, distortion, and temporary hearing loss producing additional interference with reception. The effectiveness of these acoustic maskers varies with the frequency content of the noise and with the ratio of the signal level to the noise level (S/N). In ISS, concern with the masking of the caution and warning signals in modules with higher noise levels has led to review of

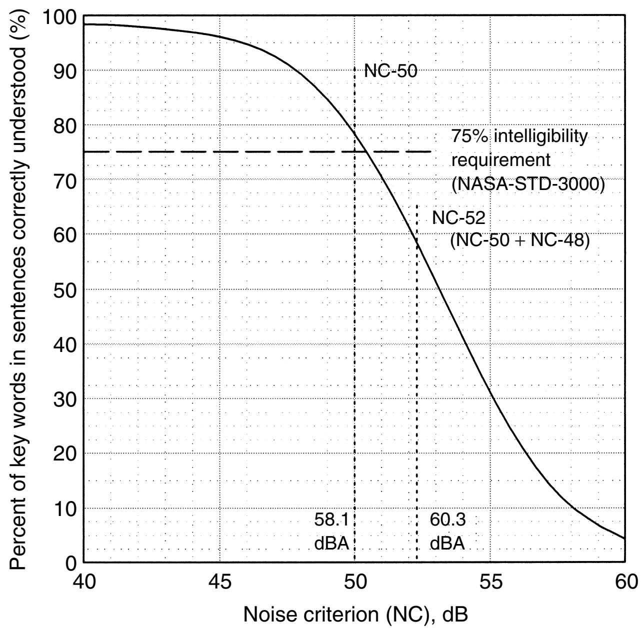


FIGURE 5-12 Recommendations for noise levels in the Space Shuttle based on the percent of key words in sentences correctly understood (Articulation Index) as function of the noise criterion. (From Pearsons KS. *Recommendations for noise levels in the space shuttle.* Bolt, Beranek, and Newman Report, BBN Job No. 1571160. February, 1975.)

military and international standards, analyses, and testing to ensure signals can be heard with confidence.

The speech signal level must be greater than the noise level at the ear for good intelligibility. Intelligibility, as a function of the signal to noise (S/N) ratio, varies with the type of speech material. Speech intelligibility for familiar phrases is approximately 0% correct at −12 dB S/N and greater than 95% correct at 0 dB S/N (range of 12 dB). Intelligibility for nonsense syllables is also 0% correct at −12 dB S/N ratio, but requires approximately +15 dB S/N to exceed 95% correct. Both spectra and levels of aerospace noises must be considered to minimize masking of the speech signal and to ensure successful communication. The World Health Organization recommends an S/N of 15 dB for full sentence intelligibility in listeners with normal hearing (52).

Electronic Audio Communications

Audio communication systems are optimized for human speech, which is vulnerable to environmental, personal, and message elements in aerospace environments. Noise, both acoustic and electrical, is the most disruptive factor. Acceleration, whole-body vibration, artificial atmospheres, high workloads, and threats to personal safety can also alter communications. Operator speech performance is influenced by accents, dialects, word usage, hearing loss, amount and type of communication experience, and even emotional state of the individual. Messages are altered by speech elements that include message set, type of material, vocabulary size, unexpected terms, and infrequently used phrases.

The performances of talkers and listeners vary greatly under the same communication situations. These variances can be increased to unsatisfactory levels in such hostile conditions as intense noise, fatigue, high workload, and jammed audio communications. It is important that communicators be trained for the environments in which they communicate. Inexperienced subjects of both genders showed dramatic improvements with voice communications in high-level noise and with electronically jammed speech as a result of training (53). Talkers and listeners steadily improve when they use a communication system over time. Those who were initially the best communicators appear to remain the best over time.

Noise Regulations, Measurements, and Control

Noise Regulations

Occupational Noise Exposure Regulations

The most common noise exposure criterion for prevention of hearing loss is a TWA of 85 dBA for 8 hours with a 3-dB/doubling exchange rate (30). When a 3-dB exchange rate is used, a doubling of the 85-dBA noise level (to 88 dBA) halves the allowable exposure time from 8 hours to 4 hours. A halving of the 85-dBA level to 82 dBA doubles the permissible exposure time from 8 hours to 16 hours. This criterion is used worldwide and by most U.S. agencies except for OSHA and the U.S. Navy. OSHA currently uses 90 dBA for 8 hours with a 5-dB/doubling criterion as its permissible exposure level and the U.S. Navy is using a criterion of 84 dBA for 8 hours with a 4-dB/doubling exchange rate. The goal in most hearing conservation programs is to keep the exposure less than the criterion TWA. The risk of NIHL can be reduced with the use of hearing protection devices (HPDs), limiting exposure times, and noise controls (such as increasing the distance between the worker and the sound source or engineering modification) to reduce the overall sound levels. HPDs need to be provided during exposure to noise levels of 85 dBA or greater. NASA considers occupational exposure to an 8-hour TWA of 85 dBA or greater to be hazardous to hearing. In space flight, constant sound levels of 85 dBA or greater are considered hazardous, regardless of the duration of exposure.

Space Vehicle Noise Limits

An OASPL of 68 dBA was applied as a common continuous noise limit for operating systems in all areas of the Orbiter and manned laboratories. Payloads had to meet the equivalent of 58 dBA individually with their total noise added to the systems noise level to determine overall noise. Intermittent limits were levied on payloads and government furnished equipment (GFE). Space Shuttle Orbiter flight rules were implemented that required actions to power off noise sources or take actions such as wearing hearing protection, when levels reached 74 dBA for a 24-hour TWA (54).

ISS continuous noise limits for the habitable space in the U.S. segment have been set at NC-50 (Figure 5-13). Maximum SPLs for each individual payload rack are established at NC-40, and the total complement of payloads

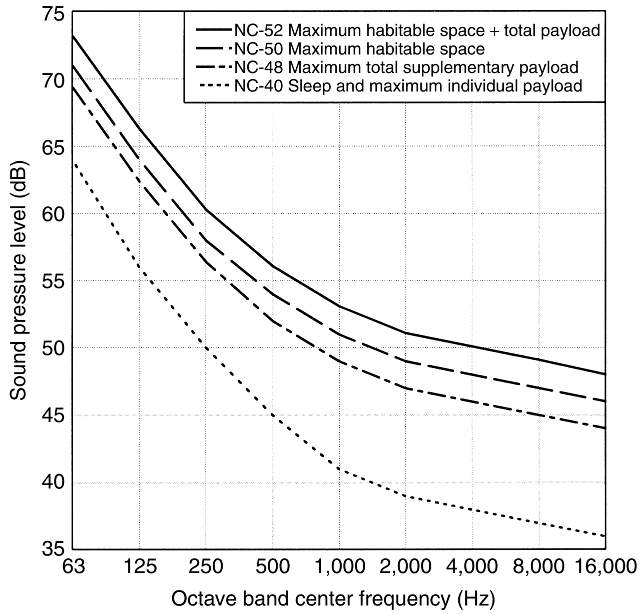


FIGURE 5-13 International Space Station (ISS) continuous noise specifications.

is limited to NC-48. The resultant maximum sound levels for the modules plus payloads are constrained by the NC-52 levels in Figure 5-13 (approximate total of NC-50 + NC-48). Intermittent noise limits were implemented for the payloads, but were set lower than in the Orbiter because of significant differences in flight duration and configuration, and the need for ISS to provide levels acceptable for long-term communications, habitability, and health. Flight rules require the crew to wear hearing protection when levels exceed 66 dBA for a 24-hour TWA. For 24-hour exposures, at the listed dBA levels the specified wear times are 67 dBA for 2 hours, 68 dBA for 7 hours, 69 dBA for 11 hours, 70 dBA for 14 hours and so on, until above 77 dBA wearing hearing protection full time is required (55). Hazardous overall noise limits adopted in the NASA standards are for continuous noise levels during flight to be limited by 85 dBA at the crewmember's ear (43). Impulse sound, a change in SPL of more than 10 dB in 1 second or less, is not allowed to exceed 140 dB peak SPL (43). Noise from hardware associated with accepted short-term operations during launch, entry, or burns should be kept lower than 105 dBA according to recent NASA efforts for the Exploration Mission vehicles (56). This level was based on a 1.5-minute exposure. A summary of acoustic requirements recommended in space flight programs is provided in the section on Acoustics in Reference (57).

Noise Measurements

The basic instrumentation components used for sound measurements consist of a microphone, an amplifier, and an analysis device. The sound level meter (SLM) contains these components and displays SPLs referenced to 20 μPa. It provides a single-number overall reading of the SPL in the audible frequency range. Most SLMs contain three standardized electrical weighting or filter networks (A, B, and C).

The SLM is used for general purpose and survey work such as continuous monitoring of noise at a workstation, the identification of noise hazardous areas, or for measurements of acoustic compliance in work spaces. When noise conditions exceed exposure criteria and noise control measures are indicated, an analysis of the SPL as a function of frequency is usually required. Instruments that perform this function are frequency analyzers, which commonly assess levels in one octave, one-third octave, or constant frequency bandwidths and may be used independently or in combination with SLMs. Some higher-end SLMs have the capability to perform a frequency analysis. Frequency analyzers are imperative because effective noise control measures deal with the problem areas in the frequency spectrum identified by octave band, one-third octave band, or constant bandwidth descriptions of the sound. In the Orbiter, SLMs were periodically flown and used to measure the acoustic levels and spectra. In the ISS, SLMs are used on-orbit, in periodic surveys to characterize the noise in preestablished measurement locations within the modules.

Personal noise dosimeters are small, lightweight devices worn by individuals to indicate their exposure to noise over a specified time period, typically for hearing conservation purposes. A dosimeter consists of a microphone, a unit that integrates acoustic energy over time, and a readout that displays the exposure or dose at the time the unit is read. A noise dosimeter is designed with one or more built-in displays that can report TWA levels and noise exposure doses in terms of the criteria used by the relevant regulatory standard. Various commercially available noise dosimeters differ somewhat in operation and readout, with some providing continuous 24-hour monitoring important for long-duration space flights. The general principle of operation is essentially the same among dosimeters, with the final output indicating the percentage of the allowable daily noise dose actually experienced by the individual wearing the unit. In the Orbiter, modified commercial dosimeters were periodically flown to record the crew exposure levels/dosage. In the ISS, similar dosimeters are used on-orbit in a crew-worn mode of operation to determine the crew dosage, and are affixed in local areas of the module to determine the average levels at those locations. The dosimeters can be used in an SLM mode or for readout of the maximum level experienced during the dosimeters operation.

Noise Control

Environmental Noise Control

In atmospheric flight, external noises originate from propulsion units and aerodynamic flow over the fuselage. In aerospace vehicles, internal noise is generated by fans, air conditioners, blowers, and pumps. These noises must be controlled. Noise control of the source and the pathways that lead to the receiver is a well-established engineering discipline that is amenable to quantitative analysis and design. Noise reduction is usually not designed to satisfy optimum comfort criteria but to guarantee allowable safe exposure conditions and communication capabilities for the crewmembers. In ISS, a substantial effort is made in designing quiet payloads and controlling the complement that is flown or used at any time during a mission. The fans and pumps in payloads are prime contributors to cabin noise levels in ISS. GFE such as exercise equipment (treadmill, bicycle, or resistive device), personal hygiene equipment (hair dryers and shavers) add intermittent noise and affect overall exposure. Design efforts are focused on developing quieter equipment, adding mufflers at the inlet and outlet of fans, and structurally isolating fans, pumps, and compressors through mechanical isolators. The noise level of most modules has been controlled close to NC-52, which is considered the equivalent of 60 dBA. The effectiveness of overall ISS noise control is enhanced by implementation of noise control plans, good design requirements, testing of hardware for compliance, constant oversight of compliance, and by participation in module design reviews and review meetings with the suppliers of modules, payloads, and other hardware. A summary of ISS noise control approaches and examples of design implementation is provided in the section **Noise Control** in Goodman and Grosveld (58).

Personal Protective Equipment

The SLM and dosimeters previously discussed are used to determine acoustic levels or dosage that personnel are exposed to and provide a basis for hearing protection needs. In many operational noise environments, the use of passive personal HPDs such as earplugs, earmuffs, or helmets are the only feasible means of reducing noise to an acceptable level at the ears. However, some HPDs can produce pressure points or become uncomfortable, produce infections, or may require removal to allow communications. The attenuation achieved by individuals under operational conditions varies considerably among the different devices depending on factors such as the selection, effectiveness, use, and care of the hearing protectors. All personnel should receive periodic training on HPDs and hearing conservation. Representative ranges of mean attenuation values of various types of HPDs are summarized in Figure 5-14. The mean values shown in the figure express the real-ear attenuation determined in the laboratory by a standardized psychophysical method with human subjects wearing the devices. The average attenuation values are extended to cover 98% of the population by subtracting two standard deviations from the mean values. Even with maximum attenuation, intense levels of sound can bypass the HPDs, enter the head and upper torso through areas not covered by the protectors, and reach the inner ear through tissue and bone conduction.

The performance of an HPD can be conveniently described by a single-number rating, such as the noise reduction rating (NRR) required by the Environmental Protection Agency (EPA) in its regulation on the noise

Type of protection	Third-octave band center frequencies (Hz)						
	125	250	500	1,000	2,000	4,000	8,000
	Attenuation (dB)						
Earplugs (Premolded, user formable)	10–30	10–30	15–35	20–35	20–40	30–45	25–45
Foam earplugs (Varies with depth of insertion)	20–35	20–35	25–40	25–40	30–40	40–45	35–45
Earplugs (first generation custom molded)	5–20	5–20	10–25	10–25	20–30	25–40	25–40
Earplugs (Custom molded deep insertion ± 1 SD)	23–41	22–36	26–40	30–42	31–39	37–41	40–48
Semi-insert earplugs	10–25	10–25	10–30	10–30	20–35	25–40	25–40
Earmuffs/headsets (with or without communications)	5–20	10–25	15–30	25–40	30–40	30–40	25–40
Earplugs and earmuffs/headsets (in combination)	20–40	25–45	25–50	30–50	35–45	40–50	40–50
Headsets with active noise reduction	20–35	25–40	30–45	Identical to earmuffs above 1,000 Hz			
Helmets	0–15	5–15	15–25	15–30	25–40	30–50	20–50
Space helmets (total head enclosure)	8–12	10–15	15–25	15–30	25–40	30–50	30–60

FIGURE 5-14 The ranges of attenuation (in dB) shown for good hearing protection devices represent the approximate minimum and maximum protection available.

labeling of hearing protectors (59). The effective A-weighted noise exposure for a person wearing the device is estimated by subtracting the NRR from the measured C-weighted level of the noise. For example, a wearer of a device with an NRR of 25 dB is exposed to an effective noise level at the ear of 80 dB when the C-weighted level of the measured noise is 105 dB. When only A-weighted sound level is measured, the effective noise exposure level is obtained by subtracting the NRR from the measured noise, as well as subtracting an additional 7 dB to compensate for the A-weighting. A more accurate exposure is obtained by performing the calculations on an octave band basis. Field studies have revealed that, owing to inadequate earplug insertion and fit, users often achieve as little as 33% of the attenuation reported from laboratory studies, or the NRR. Consequently, a earplug's NRR is often derated owing to factors in the workplace such as lack of training, incorrect size and fit, poor compliance, deterioration of devices, and modifications to the devices by personnel. The maximum noise reduction achievable with the best HPDs is not typically obtained because of air leaks, vibration of the protector, and sound passing through the materials.

The EPA has received funding and approval to update the NRR in 2007. A two-number range (perhaps called *noise reduction range*) may be adopted that expresses the 20th and 80th percentile of attenuation among users. The rating is designed to be subtracted from A-weighted noise levels, not C-weighted, as the current NRR requires.

Active noise reduction (ANR) HPDs reduce the low-frequency noise at the ear under the earmuff by means of noise cancellation. The ANR system cancels a significant amount of the low-frequency noise below approximately 1,000 Hz, as shown in Figure 5-14. The ANR system detects the noise at the headset, processes it, and produces a sound field that creates destructive interference reducing the level of the perceived noise. ANR headsets provide an improved quality speech signal resulting in better intelligibility, increased comfort, less hearing loss, and less fatigue than the same headset with only passive attenuation. ANR headsets are widely used in general aviation aircraft. Some ANR headsets can be customized for personnel with non-normal hearing. The passive attenuation is increased, the ANR boosted, and the band-pass and gain of speech configured to match the user's residual hearing. In ISS, where noise levels in some modules are high, the use of various types of insert earplugs and ANR headsets has provided adequate hearing protection. To ease concerns with infection or discomfort with HPDs, a variety of HPDs are used on-board.

Noise canceling microphones significantly reduce low-frequency noise without affecting sensitivity to the speech signal. Improved voice communications effectiveness is needed in high noise level aerospace environments, such as helicopters and fighter jets. The use of insert earplugs under communications headsets and helmets often achieves the additional voice communications and sound protection required in these very high level noise environments. The insert earplug provides equal attenuation of the noise and the speech signal. Then, the level of the voice signal is increased while the level of the noise remains unchanged. Significant improvements are achieved in the speech-to-noise ratio at the ear and in the speech intelligibility. Noise-excluding personal equipment is not always adequate for satisfactory communications when used in environments with the highest levels of noise. However, in most other noise environments the equipment provides satisfactory voice communications. The communication earplug (CEP) is a technology featuring two small sound transducers that are connected to the voice communication system and are paired with foam ear tips, which provide passive noise attenuation. The mini-CEP is even smaller, more comfortable, and more rugged, and fits completely in the ear canal providing approximately 30 dB of noise attenuation. Because the signal is routed to the medial side of the hearing protector, rather than peripherally, speech intelligibility is significantly greater compared to passive or ANR headsets. Helicopter and fighter jet cockpit environments greatly benefit from the CEP technology.

Speech-Based Control, Response, and Localization

Aerospace operations remain a fertile area for applications of speech-based control and voice response technologies. Speech-based systems continue to be evaluated in atmospheric and space flight environments. Excellent comprehensive contemporary reports on *The Technology of Speech-Based Control* (60) and *Applications of Speech-Based Control* (61) in aerospace environments are available.

Automatic Speech Recognition

Human speech is a very complex and sophisticated acoustic signal. Automatic speech recognition (ASR) systems must substantially reduce and transform elaborate speech code to very small signals recognizable by the systems while preserving the important speech code information. All speech recognition systems are similar in that they acquire the speech signal, digitally process the signal, and transform the processed speech signal into a pattern that is matched to the patterns of the recognition system. This process is successful in benign environments but is very vulnerable to disruption and masking, particularly by acoustic noise. Recognition rate decreases as noise increases. ASR systems are continually being evaluated for human operator interfaces to minimize excessive workloads and increase overall efficiency. Multiple visual and manual tasks, time-critical responses, and highly specialized situational actions can constitute a threat to safety as well as mission accomplishment. Speech-based control as a supplement to conventional controls is becoming more common. Speech recognition depends heavily on speaker vocal traits, quality of training, and speaker assimilation. Accent in any language degrades the performance of present day systems that must have a built-in feedback loop to learn to recognize the accent. Accent is a concern and a challenge in military multinational forces, commercial applications on personal computers, the telephone network, and in air traffic control.

Voice control technology is included in the US multiservice joint strike fighter (JSF) aircraft. Speech input is incorporated in the single-seat European fighter aircraft EF2000 and is used for control of displays, radar, radios, target designation, navigation aids, and other functions. Pilots assessing the EF2000 program regard speech recognition as "essential to the safe and efficient operation of the aircraft" (61). Stress experienced by the crew may negatively influence the speech signal. The gravity-load effect on speech production is a relative factor. Highly experienced personnel can speak relatively normally at up to 5-G sustained acceleration with only approximately 5% loss in recognizer performance. Inexperienced subjects may encounter 30% loss in recognizer performance even at low sustained acceleration levels. In addition, G-protection requires increasing the breathing gas pressure in the oxygen mask by as much as 50 mm Hg or more, which affects speech production. Vibration is present on most aerospace vehicles; however, it is a dominant problem for speech recognition in rotary wing aircraft. Reliability or correct word recognition may vary from 95% to more than 99% under favorable conditions, but may drop to essentially 0% under the most severe conditions. Pilots of both fixed- and rotary wing aircraft consider that positive speech recognition experiences increase their capabilities while decreasing their workload.

One of the challenges of using voice input for space applications continues to be reduced recognition rates due to the relatively high ambient noise levels within a spacecraft. In the 1980s, the Orbiter successfully used voice input/output as the main method for astronauts to interact with the five flight computers. A commercially available speaker-dependent speech recognition system was used as an alternative to the manual keyboard. In 1990, the operational effectiveness of voice control in space systems was further demonstrated. Two astronauts successfully panned, tilted, and focused four TV cameras in the payload bay. In 2005, a NASA-funded research project resulted in the development of a speech enhancement system based on Independent Component Analysis. The custom microphone developed as part of the system filters noise from a voice signal input, thereby enhancing speech recognition rates. This system is being tested for use with a variety of other NASA projects, including integration with a head mounted display (HMD).

Machine Voice Response

Voice response systems are already deeply imbedded in the commercial marketplace. Microprocessors provide a wide variety of preprogrammed words and phrases in typical male or female voices. Among the aerospace applications of machine voice responses are advisory, validation, and warning functions. Present microprocessor-type systems are highly flexible and can be developed to be adaptive in terms of message management, including priorities. The application of an adaptive voice response database involves the effective integration of voice warning with nonvoice warning signals, visual displays, annunciator indicators, and the audio communications function. Crew on commercial and military aircraft benefit from the annunciation voices and verbal resolution instructions from warning systems such as the Traffic Alert and Collision Avoidance System (TCAS) minimizing the chances of midair collisions between aircraft. The Terrain Avoidance Warning System/Enhanced Ground Proximity Warning System (TAWS/EGPWS) alerts pilots of such hazards as wind shear, excessive glide slope, and unsafe terrain clearance. Aircraft-related warnings such as stall, fire, overspeed, altitude, and autopilot disconnect are incorporated in the Central Aural Warning System (CAWS). In the Space Shuttle Orbiter, auditory alerts and fault messages are generated in response to sensor readings exceeding preset limits.

Localization

A relatively new technology, 3-D audio, enables localization information to be added to audio signals perceived over headphones. Audio signals such as voice communication, target location, warning signals, and aircraft advisories are recognized as coming from the location of their source relative to the receiving operator. Comprehension of competing messages has been significantly improved by 3-D separation. Localization of sounds is a natural, automatic response in humans. Operator use of 3-D audio technology is also natural, requires no training, and is not affected by ambient noise unless it is masked. This technology reduces workload and adds valuable precision to aircrew performance.

Virtual prototyping allows designers to view and analyze prototypes of aircraft and space vehicle interiors using 3-D virtual reality technology (62). Noise sources can be simulated on the basis of their individual or collective characteristics and the sound quality of the acoustic environment and response of the crewmembers can be evaluated before and during the design and manufacturing stages of the actual vehicle. A noise mitigation process, if required, can be applied to individual sources or any combination thereof and allows for relocation or acoustic control of offending contributors. The International Space Station Environment Simulator (ISSES) is a virtual reality development that uses sound rendering over headphones and speaker systems to simulate potential, arbitrary ISS acoustic environments in real time (63). The design approach allows the prospective crewmember or analyst to move to different locations inside an ISS mockup and hear a combination of nonspatial reverberant noise, such as the air handling system, as well as direct sound contributions associated with being in the close proximity of specific rack equipment, such as fans or compressors. The consequences of noise mitigation measures, including the treatment and control of the noise sources, paths, and receiving space, could be simulated and analyzed to assess compliance with the noise requirements. The subjective, human response to the noise may be evaluated through binaural simulation, which represents the sound as heard independently by the left and the right ear and includes interaural signal time, intensity differences, and the acoustic scattering about the head, pinna, and torso (64).

Virtual prototyping may help to incorporate acoustics in the early design and assessment of future aerospace acoustic environments.

ACKNOWLEDGMENTS

The authors of the fourth edition graciously acknowledge the contributions of Dr. Richard W. Danielson, the previous authors Dr. Henning von Gierke and Charles W. Nixon, and their many colleagues and associates whose efforts are referenced in this chapter. Their pioneering research has laid the foundation for defining human response to vibration and noise, particularly in aerospace environments.

REFERENCES

1. International Standards Organization (ISO). *Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements. ISO 2631-1:1997(E)*, 1997.
2. Guignard JC, King PF. *Aeromedical aspects of vibration and noise. AGARD-AG-151*, 1972.
3. Smith SD. Collection and characterization of pilot and cockpit buffet vibration in the F-15 aircraft. *SAFE J* 2002;30(3):208–218.
4. Griffin MJ. *Handbook of human vibration*. London: Academic Press, 1990.
5. Coermann RR. *The mechanical impedance of the human body in sitting and standing position at low frequencies.* ASD Technical Report 61–492. WPAFB, Ohio: Aeronautical Systems Division, Air Force Systems Command, United States Air Force, 1961.
6. Vogt HL, Coermann RR, Fust HD. Mechanical impedance of the sitting human under sustained acceleration. *Aerosp Med* 1968;39(7):675–679.
7. Smith SD. Modeling differences in the vibration response characteristics of the human body. *J Biomech* 2000;33(11):1513–1516.
8. von Gierke HE, Nixon CW. Effects of intense infrasound on man. In: Tempest W, ed. *Infrasound and low frequency vibration*. New York: Academic Press, 1976; 115–150.
9. Mohr GC, Cole JN, Guild E, et al. Effects of low frequency and infrasonic noise on man. *Aerosp Med* 1965;36(9):817–824.
10. Smith SD. The effects of airborne vibration on human body vibration response. *Aviat Space Environ Med* 2002;73(1):36–45.
11. Magid EB, Coermann RR, Ziegenruecker GH. Human tolerance to whole body sinusoidal vibration. *Aerosp Med* 1960;31:915–924.
12. Hood WB, Murray RH, Urschel CW, et al. Cardiopulmonary effects of whole-body vibration in man. *J Appl Physiol* 1966;21(6):1725–1731.
13. de Oliveira CG, Simpson DM, Nadal J. Lumbar back muscle activity of helicopter pilots and whole-body vibration. *J Biomech* 2001;34:1309–1315.
14. Lopez-Lopez JA, Vallejo P, Rios-Tejada F, et al. Determination of lumbar muscular activity in helicopter pilots: a new approach. *Aviat Space Environ Med* 2001;72(1):38–43.
15. Harris SC, Shoenberger RW. Combined effects of broadband noise and complex waveform vibration on cognitive performance. *Aviat Space Environ Med* 1980;51(1):1–5.
16. Smith SD, Smith JA. Head and helmet biodynamics and tracking performance in vibration environments. *Aviat Space Environ Med* 2006;77(4):388–397.
17. Huddleston HF. *Human performance and behaviour in vertical sinusoidal vibration*. IAM Report No. 303. Farnborough, England: Institute of Aviation Medicine, 1964.
18. Butler BP. *Helmeted head and neck dynamics under whole-body vibration*. Doctoral Thesis, University of Michigan, Ann Arbor, 1992.
19. Wells MJ, Griffin MJ. Benefits of helmet-mounted display image stabilisation under whole-body vibration. *Aviat Space Environ Med* 1984;55(1):13–18.
20. Temple WE, Clarke NP, Brinkley JW, et al. *Man's short-time tolerance to sinusoidal vibration. AMRL-TR-65-96,* Wright-Patterson AFB, Ohio: Aerospace Medical Research Laboratories, 1965.
21. Taub HA. *The effects of vibration on dial reading performance. AMRL-TDR-64-70 (AD 603 963),* Wright-Patterson AFB, Ohio: Aerospace Medical Research Laboratories, 1964.
22. Taub HA. *Dial-reading performance as a function of frequency of vibration and head restraint system. AMRL-TR-66-57,* Wright-Patterson AFB, Ohio: Aerospace Medical Research Laboratories, 1966.
23. Shoenberger RW. *Investigation of the effects of vibration on dial reading performance with a NASA prototype Apollo helmet*. *AMRL-TR-67-205,* Wright-Patterson AFB, Ohio: Aerospace Medical Research Laboratories, 1968.
24. American National Standards Institute (ANSI). *Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements. ANSI S3.18–2002*, Acoustical Society of America, 2002.
25. Smith SD. Seat vibration in military propeller aircraft: characterization, exposure assessment, and mitigation. *Aviat Space Environ Med* 2006;77(1):32–40.
26. The European Union Parliament and the Council of the European Union. *On the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration). Directive 2002/44/EC,* 2002.
27. Department of Defense Design Criteria Standard. *Human engineering*. *MIL-STD-1472F*, 23 August 1999.
28. National Aeronautics and Space Administration. *Man-systems integration standards. NASA STD-3000*, Revision B, July, 1995.
29. American Conference of Governmental Industrial Hygienist, Inc. TLVs, and BEIs, Cincinnati, OH. ACGIH, 2003.
30. Air Force Occupational Safety and Health Standard. *Occupational noise and hearing conservation program. AFOSHSTD 48-20*, 30 June 2006.
31. American National Standards Institute (ANSI). *Acoustical terminology*. *ANSI S1.1–1994*, Acoustical Society of America, 1994:2. (Revision 2004).
32. Harris CM, ed. *Handbook of acoustical measurements and noise control*, 3rd ed. New York: McGraw-Hill, 1991.
33. Heller H, Dahlen H, Dobrzynski W. Acoustics of ultralight aircraft. *J Aircr* 1990;27(6):529–535.
34. Goodman JR. International space station acoustics. *Proceedings of NOISE-CON 2003.* Cleveland, June 2003.
35. Beranek LL. Criteria for noise and vibration in communities, buildings, and vehicles. In: Beranek LL, Ver I, eds. *Noise and vibration control engineering*. New Jersey: John Wiley & Sons, 1992.
36. American National Standards Institute (ANSI). *Methods for the calculation of the articulation index (AI). ANSI S3.5–1969 R1986*, Acoustical Society of America, 1986.
37. American National Standards Institute (ANSI). *Method for calculation of the speech intelligibility index. ANSI S3.5–1997*, Acoustical Society of America, 1997.
38. Steeneken HJM, Houtgast TA. Physical method for measuring speech transmission quality. *J Acoust Soc Am* 1980;67: 3318–3326.
39. International Electro-Technical Commission. *Sound system equipment Part 16: objective rating of speech intelligibility by speech transmission index. IEC 60268-16th Edition.* Geneva: International Standards Organization, 1998.
40. American National Standards Institute (ANSI). *Method for measuring the intelligibility of speech over communication systems. ANSI S3.2–1989*, Acoustical Society of America, 1989.

41. Nixon CW. Excessive noise exposure. In: Singh S, ed. *Measurement procedures in speech, hearing, and language*. Baltimore: University Park Press, 1975.
42. Kryter KD. *The effects of noise on man*. New York: Academic Press, 1970.
43. NASA Johnson Space Center. *Man-system integration standard, NASA STD-3000*, Volume I, Part A, 1995.
44. Humes LE, Joellenbeck LM, Durch JS. *Noise and military service: implications for hearing loss and tinnitus*. National Academies Press, 2005.
45. International Standards Organization (ISO). *Acoustics, determination of occupational noise exposure and estimation of noise-induced hearing impairment*. *ISO 1999-2nd ed 1990.* International Organization for Standardization, Geneva, Switzerland, 1990.
46. Kent SJ, Tolen GD, von Gierke HE. Analysis of the potential association between noise-induced hearing loss and cardiovascular disease in USAF air crew members. *Aviat Space Environ Med* 1986;57:348–361.
47. U.S. Department of labour, Occupational Safety and Health Administration Regulations (Standards-29CFR). *Occupational Noise Exposure*, 29 CFR 1910.95, 1983.
48. Department of Defense. *DOD hearing conservation program*, Instruction 6055.12, 1996.
49. NASA. *NPR 1800.1, Occupational Health*, 2006.
50. Harris CS. *Effects of noise on health*. *AL/OE-TR-1997-0077*, Wright-Patterson Air Force Base, Ohio: Noise Effects Branch, USAF Armstrong Laboratory, 1997.
51. Pearsons KS. *Recommendations for noise levels in the space shuttle*. Bolt, Beranek, and Newman report, BBN Job No. 1571160. February, 1975.
52. Berglund B, Lindvall T, Schwela DH. *Guidelines for community noise*. World Health Organization, April 1999.
53. Nixon CW, McKinley RL, Moore TJ. Increase in jammed word intelligibility due to training of listeners. *Aviat Space Environ Med* 1982;53(3):239–244.
54. NASA Johnson Space Center. *Flight directors office volume A, space shuttle operational flight rules*, *Flight Rule-A-13-29*, 2007.
55. NASA Johnson Space Center. *Flight directors office volume B, ISS generic operational flight rules*, *Flight Rule-B-13-152A.1*, 2007.
56. NASA Johnson Space Center. *Constellation program human-systems integration requirements*, *CxP70024*, 2006.
57. Goodman JR, Grosveld FW. Acoustics. In: Musgrave G, Larsen A, Sgobba T, eds. *Principles of safety design for space systems*, Oxford: Elsevier Science & Technology Books, February 2008.
58. Goodman JR, Grosveld FW. Noise control design. In: Musgrave G, Larsen A, Sgobba T, eds. *Principles of safety design for space systems*. Oxford: Elsevier Science & Technology Books, February 2008.
59. U.S. Environmental Protection Agency. *Noise labeling requirements for hearing protectors*. Washington, DC: *Federal Register*, 42 (190), (40 CFP Part 211), 1979:20460, 56120–56147.
60. Anderson TR. *The technology of speech-based control*. *RTO-EN-3, NATO, RTO, BP25*, Neuilly-Sur-Seine Cedex, France, 7–8 October 1998.
61. Anderson TR. *Applications of speech-based control*. *RTO-EN-3, NATO, RTO, BP25*, Neuilly-Sur-Seine Cedex, France, 7–8 October 1998.
62. Lalime AL, Johnson ME, Grosveld FW, et al. Computationally efficient binaural simulation of structural acoustic data. Paper 77, *Proceedings of the Eighth International Conference on Recent Advances in Structural Dynamics*. Southampton, July 14–16, 2003.
63. VerHage JE, Sandridge CA, Qualls GD, et al. ISS radiation shielding and acoustic simulation using an immersive environment. *Immersive Projection Technology 2002 Symposium*. Orlando, March 24–25, 2002.
64. Grosveld FW. *Binaural simulation experiments in the NASA Langley structural acoustics loads and transmission facility*. *NASA/CR-2001-211255*, Hampton, Virginia, December 2001.

RECOMMENDED READINGS

Berger EH, Ward WD, Morrill JC, et al. *Noise and hearing conservation manual*, 4th ed. Fairfax: American Industrial Hygiene Association, 1995.

Burns W. *Noise and man*. Philadelphia: JB Lippincott Co, 1968.

Fastl H, Zwicker, E. *Psychoacoustics: facts and models*, *Springer Series in Information Sciences*. New York: Springer-Verlag New York, 2006.

Griffin MJ. *Handbook of human vibration*. London: Academic Press, 1996.

Guignard JC, King PE. *Aeromedical aspects of vibration and noise. AGARD AG-151*. NATO, London: Technical Editing Reproduction LTD, 1972.

von Gierke HE, Brammer AJ. Effects of shock and vibration on humans. In: Harris CM, Piersol AG, eds. *Harris' shock and vibration handbook.* New York: McGraw-Hill, 2002.

International Organization for Standardization (ISO). *Mechanical vibration and shock: evaluation of human exposure to whole-body vibration. Part 1: general requirements. ISO 2631-1*, 1997.

Kryter KD. *The handbook of hearing and the effects of noise: physiology, psychology, and public health.*San Diego: Academic Press, 1995.

Moore, BCJ, ed. *Hearing—handbook of perception and cognition*, 2nd ed. San Diego: Academic Press, 1995.

Vér IL, Beranek LL. *Noise and vibration control engineering—principles and applications*. New Jersey: John Wiley & Sons, 2006.

Yost WA, Popper AN, Fay RR, eds. *Human psychophysics*. New York: Springer-Verlag New York, 1993.

CHAPTER 6

Spatial Orientation in Flight

A. J. Parmet and W. R. Ercoline

Appearances often are deceiving.

—*Aesop*

A major purpose of aerospace medicine as a specialty is the prevention of aircraft accidents and injuries. The therapy for these conditions continues to have poor results. Injuries are often disabling and fatality rates are higher in spatial orientation accidents than other types of accidents with a 90% fatality rate (1). Only prevention truly saves lives. From the earliest days of aviation, almost all accidents were attributable to human factors. During the First World War, survival of pilots was often measured in weeks, yet combat had little to do with their deaths. Most losses were due to accidents and almost all accidents were due to spatial disorientation (SD) (2). Currently, most accidents are still overwhelmingly due to human factors and a major contributor to those accidents worldwide is SD. It is essential for the understanding of spatial orientation to comprehend how the human body interacts and interprets the environment of flight in order to provide control and prevent loss of orientation that can lead to an accident.

MECHANICS

Operators of today's and tomorrow's air and space vehicles must understand clearly the terminology and physical principles relating to the motions of their aircraft so they can fly with precision and effectiveness. These crewmembers also must have a working knowledge of the structure and function of the various mechanical and electrical systems of which their craft is comprised. This will help them understand the performance limits of their machines and facilitate troubleshooting and promote safe recovery when the machines fail in flight. So, too, must practitioners of aerospace medicine understand certain basic definitions and laws of mechanics so that they can analyze and describe the environment to which the flyer is exposed. In addition, the aeromedical professional must be familiar with the physiologic bases and operational limitations of the flyer's orientation mechanisms. This understanding is necessary to enable the physician or physiologist to speak intelligently and credibly with aircrew about SD, and to enable them to contribute significantly to investigations of aircraft mishaps in which SD may be implicated.

Motion

We shall discuss two types of physical motion: linear motion or motion of translation, and angular motion or motion of rotation. Linear motion can be further categorized as rectilinear, meaning motion in a straight line, or curvilinear, meaning motion in a curved path. Both linear motion and angular motion comprise an infinite variety of subtypes, or motion parameters, based on successive derivatives of linear or angular position with respect to time. The most basic of these motion parameters, and the most useful, are displacement, velocity, acceleration, and jerk. Table 6-1 classifies linear and angular motion parameters and their symbols, and units serve as an outline for the following discussions of linear and angular motion.

Linear Motion

The basic parameter of linear motion is linear displacement. The other parameters: velocity, acceleration, and jerk are derived from the concept of displacement. Linear displacement, x, is the distance and direction of the object under consideration from some reference point; as such, it is a vector quantity, having both magnitude and direction. The position of an aircraft located at 25 nautical miles on the 150-degree radial of the San Antonio VORTAC, for example, describes completely the linear displacement

TABLE 6-1

Linear and Angular Motion–Symbols and Units

Motion Parameter	*Linear*		*Angular*	
	Symbols	*Units*	*Symbols*	*Units*
Displacement	X	meter (m); nautical mile (= 1,852 m)	Θ	degree; radian (rad) (= 360/2π degree)
Velocity	$v, \dot{x}$	meter/second (m/s); knot ($\simeq$0.514m/s)	$\omega, \dot{\theta}$	degree/s; rad/s
Acceleration	$\bar{a}, v, \bar{x}$	m/s^2; g ($\simeq$9.81 m/s^2)	$\alpha, \dot{\omega}, \overline{\theta}$	$degree/s^2$; rad/s^2
Jerk	$\dot{j}, \dot{a}, \bar{v}, \bar{x}$	m/s^3		$degree/s^3$; rad/s^3
		g/s	$\gamma, \dot{\alpha}, \dot{\omega}, \overline{\theta}$	

of the aircraft from the navigational facility serving as the reference point. The meter (m), however, is the unit of linear displacement in the International Systems of Units (SI), and will eventually replace other units of linear displacement such as feet, nautical miles, and statute miles.

When linear displacement is changed during a period of time, another vector quantity, linear velocity, occurs. The formula for calculating the mean linear velocity, v, during time interval, Δt, is as follows:

$$v = (x_2 - x_1)/\Delta t \quad [1]$$

where x_1 is the initial linear displacement and x_2 is the final linear displacement. An aircraft that travels from San Antonio, Texas to New Orleans, Louisiana in 1 hour, for example, moves with a mean linear velocity of 434 knots (nautical miles per hour) on a true bearing of 086 degrees. Statute miles per hour and feet per second are other commonly used units of linear speed, the magnitude of linear velocity; meters per second (m/s), however, is the SI unit and is preferred. Velocity is the first derivative of displacement with respect to time, dx/dt.

When the linear velocity of an object changes over time, the difference in velocity, divided by the time required for the moving object to make the change, gives its mean linear acceleration, a. The following formula:

$$a = (v_2 - v_1)/\Delta t \quad [2]$$

where v_1 is the initial velocity, v_2 is the final velocity, and Δt is the elapsed time is used to calculate the mean linear acceleration, which, like displacement and velocity, is a vector quantity with magnitude and direction. Acceleration is therefore the rate of change of velocity, just as velocity is the rate of change of displacement. The SI unit for the magnitude of linear acceleration is meters per second squared (m/s^2). Consider, for example, an aircraft that accelerates from a complete stop to a velocity of 100 m/s in 5 seconds: the mean linear acceleration is (100 m/s − 0 m/s)/5 s or 20 m/s^2. The instantaneous linear acceleration is the second derivative of displacement or the first derivative of velocity, d^2x/dt^2, or dv/dt, respectively.

A very useful unit of acceleration is g, which for our purposes is equal to the constant g_o, the amount of acceleration exhibited by a free-falling body near the surface of the Earth—9.81 m/s^2 or 32.2 ft/s^2 (see also Chapter 4). To convert values of linear acceleration given in m/s^2 into g units, simply divide by 9.81. In the previous example in which an aircraft accelerates at a mean rate of 20 m/s^2, one divides 20 m/s^2 by 9.81 m/s^2 per g (i.e., one Earth gravity or "g" is 9.81 m/s^2 or 32.2 ft/s^2—see Equation 16) to obtain 2.04 g. NOTE: In this text we refer to the ratio of acceleration to the acceleration of a free falling body with the letter "g." Some texts use the upper case G, which is also used in physics texts to represent the universal gravitational force constant. We decided to use the lower case.

A special type of linear acceleration, radial or centripetal acceleration, results in curvilinear, usually circular, motion. This acceleration acts along the line represented by the radius of the curve and is directed toward the center of the curvature. Its effect is a continuous redirection of the linear velocity, in this case called *tangential velocity*, of the object subjected to the acceleration. Two examples of this type of linear acceleration are when an aircraft pulls out of a dive after firing on a ground target or flies a circular path during acrobatic maneuvering. The value of the centripetal acceleration, a_c, can be calculated if one knows the tangential velocity, v_t, and the radius, r, of the curved path followed:

$$a_c = v_t^2/r \quad [3]$$

For example, the centripetal acceleration of an aircraft traveling at 300 m/s (~600 knots) and having a radius of turn of 1,500 m can be calculated. Dividing $(300 \text{ m/s})^2$ by 1,500 m gives a value of 60 m/s^2, which, when divided by 9.81 m/s^2 per g, comes out to 6.12 g.

This concept of acceleration due to circular motion can also be applied to the space shuttle when it orbits the Earth. As the shuttle moves along its orbit with a predetermined translational velocity it is simultaneously falling toward the Earth at the rate determined by the gravitational pull between the Earth and the shuttle. There is a constant radial acceleration, which is equal and opposite to the acceleration that would be experienced if one could remain motionless at that same altitude. Hence, to the person in the shuttle, the net effect is zero g. This does not mean that there is no gravity or acceleration. It just means the effect of all accelerations is zero (or close to it).

One can go another step in the derivation of linear motion parameters by obtaining the rate of change of acceleration. This quantity, j, is known as *linear jerk*. Mean linear jerk is calculated as follows:

$$j = (a_2 - a_1)/\Delta t \quad [4]$$

where a_1 is the initial acceleration, a_2 is the final acceleration, and Δt is the elapsed time.

Instantaneous linear jerk is the third derivative of linear displacement or the first derivative of linear acceleration with respect to time that is d^3x/dt^3 or da/dt, respectively. Although the SI unit for jerk is m/s^3, it is generally more useful to speak in terms of g-onset rate, measured in g per second (g/s).

Angular Motion

Although we touched upon angular motion with the shuttle example earlier, it is instructional to discuss in more detail some of the nuances of angular motion. The derivation of the parameters of angular motion follows in a manner parallel to the scheme used to derive the parameters of linear motion. The basic parameter of angular motion is angular displacement. For an object to be able to undergo angular displacement it must be polarized, that is, it must have a front and back, so that it can face or be pointed in a particular direction. A simple example of angular displacement is seen in a person facing east. In this case, the individual's angular displacement is 90-degree clockwise from the reference direction, which is north. Angular displacement, symbolized by θ (theta), is generally measured in degrees, revolutions (1 revolution = 360 degrees), or radians (1 radian = 1 revolution) 2π or approximately 57.3 degrees. The radian is a particularly convenient unit to use when dealing with circular motion (e.g., motion of a centrifuge) because it is necessary only to multiply the angular displacement of the system, in radians, by the length of the radius to find the value of the linear displacement along the circular path. The radian is the angle subtended by a circular arc the same length as the radius of the circle.

Angular velocity, ω (omega), is the rate of change of angular displacement. The mean angular velocity occurring in a time interval, delta Δt, is calculated as follows:

$$\omega = (\theta_2 - \theta_1)/\Delta t \quad [5]$$

where θ_1 is the initial angular displacement and θ_2 is the final angular displacement.

Instantaneous angular velocity is $d\theta/dt$. As an example of angular velocity, consider the standard-rate turn of instrument flying, in which a heading change of 180 degrees is made in 1 minute. Then ω = (180 degrees − 0 degrees)/60 s or 3 degrees/s. This angular velocity can also be described as 0.5 revolutions per minute (rpm) or as 0.052 radians per second (rad/s) (3 degrees/s divided by 57.3 degrees/rad). The fact that an object may be undergoing curvilinear motion during a turn in no way affects the calculation of its angular velocity: an aircraft being rotated on the ground on a turntable at a rate of half a turn per minute has the same angular velocity as one flying a standard rate instrument turn (3 degrees/s) in the air at 300 knots. Because radial or centripetal linear acceleration results when rotation is associated with a radius from the axis of rotation, a formula for calculating the centripetal acceleration, a_c, from the angular velocity, ω, and the radius, r, is often useful:

$$a_c = v^2/r = \omega^2 r \quad [6]$$

where ω is the angular velocity in radians/s. One can convert readily to the formula for centripetal acceleration in terms of *tangential velocity* if one remembers the following:

$$v_t = \omega r \quad [7]$$

To calculate the centrifuge having a 10-m arm and turning at 30 rpm, Equation 6 is used after first converting 30 rpm to π (or 3.14) radians/s. Squaring the angular velocity and multiplying by the 10-m radius, a centripetal acceleration of $10\pi^2$ m/s^2 or 10.1 g is obtained.

The rate of change in angular velocity is angular acceleration, α (alpha). The mean angular acceleration is calculated as follows:

$$\alpha = (\omega_2 - \omega_1)/\Delta t \quad [8]$$

where ω_1 is the initial angular velocity, ω_2 is the final angular velocity, and Δt is the time interval over which angular velocity changes.

α, $d^2\theta/dt^2$, and $d\omega/dt$ can be used to symbolize instantaneous angular acceleration, the second derivative of angular displacement or the first derivative of angular velocity with respect to time. If a figure skater is spinning at 6 revolutions/s (2,160 degrees/s or 37.7 rad/s) and then comes to a complete stop in 2 seconds, the rate of change of angular velocity, or angular acceleration, is (37.7 rad/s)/2 s or −18.9 rad/s^2.

Although not commonly used in aerospace medicine, another parameter derived from angular displacement is angular jerk, the rate of change of angular acceleration. Its description is completely analogous to that for linear jerk, but angular rather than linear symbols and units are used.

Force, Inertia, and Momentum

Generally, it is not the linear and angular motions themselves, but the forces and torques which result in or appear to result from linear and angular velocity changes that stimulate or compromise the crewmember's physiologic mechanisms.

Force and Torque

Force is an influence that produces, or tends to produce, linear motion or changes in linear motion; it is a pushing or pulling action. Torque produces, or tends to produce, angular motion or changes in angular motion; it is a twisting or turning action. The SI unit of force is the newton (N). Torque has dimensions of force and length because torque is applied as a force at a certain distance from the center of rotation. The newton-meter (N-m) is the SI unit of torque.

Mass and Rotational Inertia

Newton's law of acceleration states the following:

$$F = ma \quad [9]$$

where F is the force applied to an object, m is the mass of the object, and a is linear acceleration. To describe the analogous situation pertaining to angular motion, the following equation is used:

$$M = J\alpha \qquad [10]$$

where M is unbalanced torque (for moment) applied to the rotating object, J is rotational inertia (moment of inertia) of the object, and α represents the angular acceleration.

The mass of an object is therefore the ratio of the force acting on the object to the acceleration resulting from the force. Mass, therefore, is a measure of the inertia of an object—its resistance to being accelerated. Similarly, rotational inertia is the ratio of the torque acting on an object to the angular acceleration resulting from that torque-again, a measure of resistance to acceleration. The kilogram (kg) is the SI unit of mass and is equivalent to 1 N/(m/s^2). The SI unit of rotational inertia is merely the N m/(radian/s^2).

Because $F = ma$, the centripetal force, F_c, needed to produce a centripetal acceleration, a_c, of a mass, m, can be calculated as follows:

$$F_c = m\,a_c \qquad [11]$$

Therefore, from Equation 3:

$$F_c = (m\,v_t^2)/r \qquad [12]$$

or from Equation 6:

$$F_c = m\,\omega^2 r \qquad [13]$$

where v_t is tangential velocity, ω represents angular velocity, and r is the radius of motion. Newton's law of action and reaction, which states that for every force applied to an object there is an equal and opposite reactive force exerted by that object, provides the basis for the concept of inertial force. Inertial force is an apparent force opposite in direction to an accelerating force and equal to the mass of the object times the acceleration. An aircraft exerting an accelerating forward thrust on its pilot causes an inertial force, the product of the pilot's mass and the acceleration, to be exerted on the back of the seat by the pilot's body. Similarly, an aircraft undergoing positive centripetal acceleration as a result of lift generated in a turn causes the pilot's body to exert inertial force on the bottom of the seat. More important, however, are the inertial forces exerted on the pilot's blood and organs of equilibrium because physiologic effects result directly from such forces.

At this point it is appropriate to introduce G, which is used to measure the strength of the gravitoinertial force environment. (NOTE: G should not be confused with G, the symbol for the universal gravitational constant, which is equal to 6.70×10^{-11} N m^2/ kg^2.) Strictly speaking, G is a measure of relative weight:

$$G = w/w_o \qquad [14]$$

where w is the weight observed in the environment under consideration and w_o is the normal weight on the surface of the Earth. In the physical definition of weight,

$$w = m\,a \qquad [15]$$

and

$$w_o = m\,g_o \qquad [16]$$

where m is mass, a is the acceleratory field (vector sum of actual linear acceleration plus an imaginary acceleration opposite the force of gravity), and g_o is the standard value of the acceleration of gravity (9.81 m/s^2). Therefore, a person having a mass of 100 kg would weigh 100 kg times 9.81 m/s^2 or 981 N on Earth (although conventional spring scales would read "100 kg"). At some other location or under some other acceleratory condition, the same person could weigh twice as much (1,962 N) and cause a scale to read "200 kg." The person would then be in a 2-G environment, or, if that person were in an aircraft, he or she would be said to be "pulling" 2 G. Consider also that because

$$G = w/w_o = m\,a/m\,g_o$$

then,

$$G = a/g_o \qquad [17]$$

Therefore, the ratio between the ambient acceleratory field (a) and the standard acceleration (g_o) can also be represented in terms of G.

Therefore, g is used as a unit of acceleration (e.g., $a_c = 8$ g), and the dimensionless ratio of weights, G, is reserved for describing the resulting gravitoinertial force environment (e.g., a force of 8 G or an 8-G load). When in the vicinity of the surface of the Earth, one feels a G force equal to 1 G in magnitude directed toward the center of the Earth. If one also sustains a G force resulting from linear acceleration, the magnitude and direction of the resultant gravitoinertial G force can be calculated by adding vectorially the 1-G gravitational force and the inertial G force. An aircraft pulling out of a dive with a centripetal acceleration of 3 g, for example, would exert 3 G of centrifugal force. At the bottom of the dive, the pilot would experience the 3-G centrifugal force in line with the 1-G gravitational force, for a total of 4 G directed toward the floor of the aircraft. If the pilot could continue the circular flight path at a constant airspeed, the G force experienced at the top of the loop would be 2 G because the 1-G gravitational force would subtract from the 3-G inertial force. Another common example of the addition of gravitational G force and inertial G force occurs during the application of power on takeoff or on a missed approach. If the forward acceleration is 1 g, the inertial force is 1 G directed toward the tail of the aircraft. The inertial force adds vectorially to the 1-G force of gravity, directed downward, to provide a resultant gravitoinertial force of 1.414 G pointing 45 degrees down from the aft direction.

Just as inertial forces oppose acceleration forces, so do inertial torques oppose acceleratory torques. No convenient derived units exist, however, for measuring inertial torque; specifically, there is no such thing as angular G.

Momentum

To complete this discussion of linear and angular motion, the concepts of momentum and impulse must be introduced. Linear momentum is the product of mass and linear velocity—m and v. Angular momentum is the product of rotational inertia and angular velocity—$J\omega$. Momentum is a quantity that a translating or rotating body conserves, that is, an object cannot gain or lose momentum unless it is acted on by a force or torque. A translational impulse is the product of force, F, and the time over which the force acts on an object, Δt (delta t), and is equal to the change in linear momentum imparted to the object. Therefore:

$$F\Delta t = m v_2 - m v_1 \qquad [18]$$

where v_1 is the initial linear velocity and v_2 is the final linear velocity.

When dealing with angular motion, a rotational impulse is defined as the product of torque, M, and the time over which it acts, Δt. A rotational impulse is equal to the change in angular momentum. Therefore,

$$M\Delta t = J\omega_2 - J\omega_1 \qquad [19]$$

where ω_1 is the initial angular velocity and ω_2 is the final angular velocity.

The above relations are derived from the law of acceleration, as follows:

$$F = m a$$
$$M = J\alpha$$

because $a = (v_2 - v_1)/\Delta t$ and $\alpha = (\omega_2 - \omega_1)/\Delta t$

Directions of Action and Reaction

A number of conventions have been used in aerospace medicine to describe the directions of linear and angular displacement, velocity, and acceleration and of reactive forces and torques. The more commonly used of those conventions will be discussed in the following sections.

Vehicular Motions

Because space is three-dimensional, linear motions in space are described by reference to three linear axes and angular motions by reference to three angular axes. In aviation, it is customary to speak of the longitudinal (fore-aft), lateral (right-left), and vertical (up-down) linear axes and the roll, pitch, and yaw angular axes, as shown in Figure 6-1.

Most linear accelerations in aircraft occur in the vertical plane defined by the longitudinal and vertical axes, because thrust is usually developed along the former axis and lift is usually developed along the latter axis. However, that is changing. Aircraft capable of vectored thrust are now operationally used such as the F-22 and vectored-lift aircraft such as the CV-22 (tilt-wing rotorcraft) have been in operation for several years. This will create an even more threatening environment for SD.

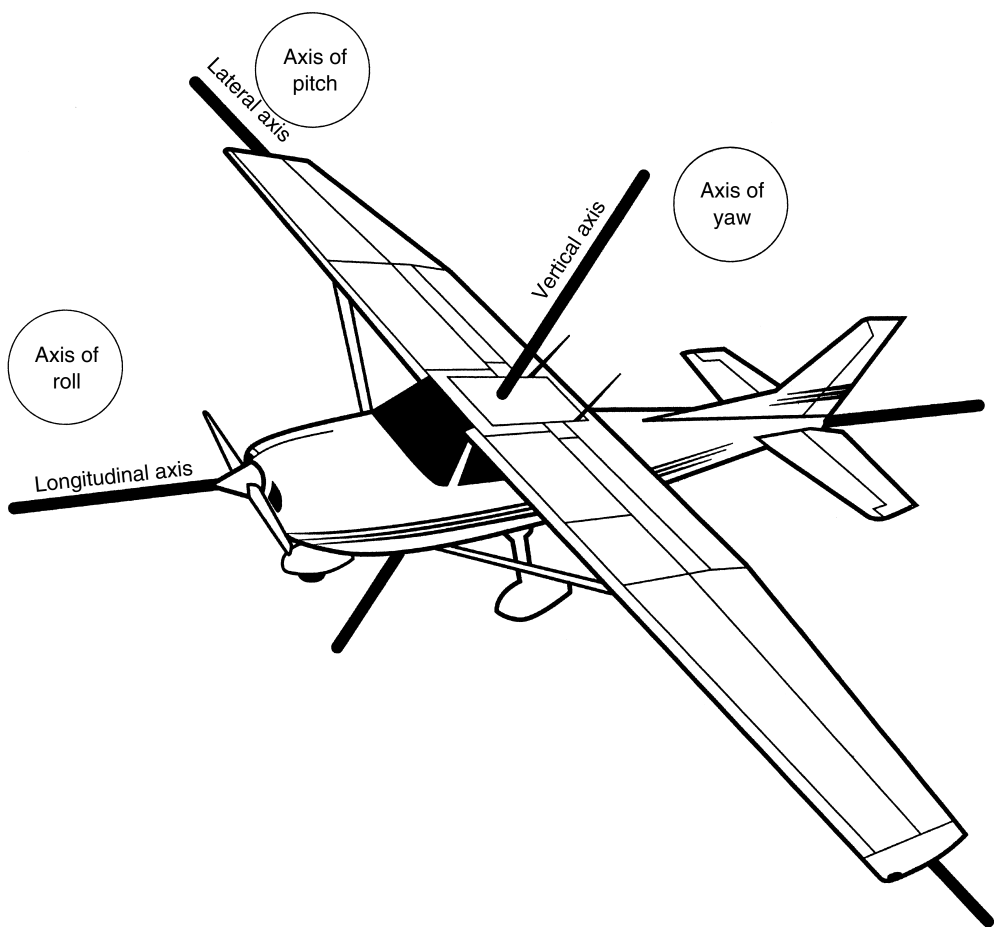


FIGURE 6-1 Axes of linear and angular aircraft motions. Linear motions are longitudinal, lateral, and vertical, and angular motions are roll, pitch, and yaw.

Most angular accelerations in aircraft occur in the roll plane (perpendicular to the roll axis) and, to a lesser extent, in the pitch plane. Angular motion in the yaw plane is very limited in normal flying, although it does occur during spins and several other acrobatic maneuvers. Certainly, aircraft and space vehicles of the future can be expected to operate with considerably more freedom of both linear and angular motion than do those of the present.

Physiologic Acceleration and Reaction Nomenclature

Figure 6-2 depicts a practical system for describing linear and angular accelerations acting on humans (3). This system is used extensively in aeromedical scientific writing. In this system, a linear acceleration of the type associated with a conventional takeoff roll is in the $+a_x$ direction, that is, it is a $+a_x$ acceleration. Braking to a stop during a landing roll results in $-a_x$ acceleration. Radial acceleration, the type usually developed during air combat maneuvering, is $+a_z$ acceleration: foot-to-head. The right-hand rule for describing the relationships between three orthogonal axes aids recall

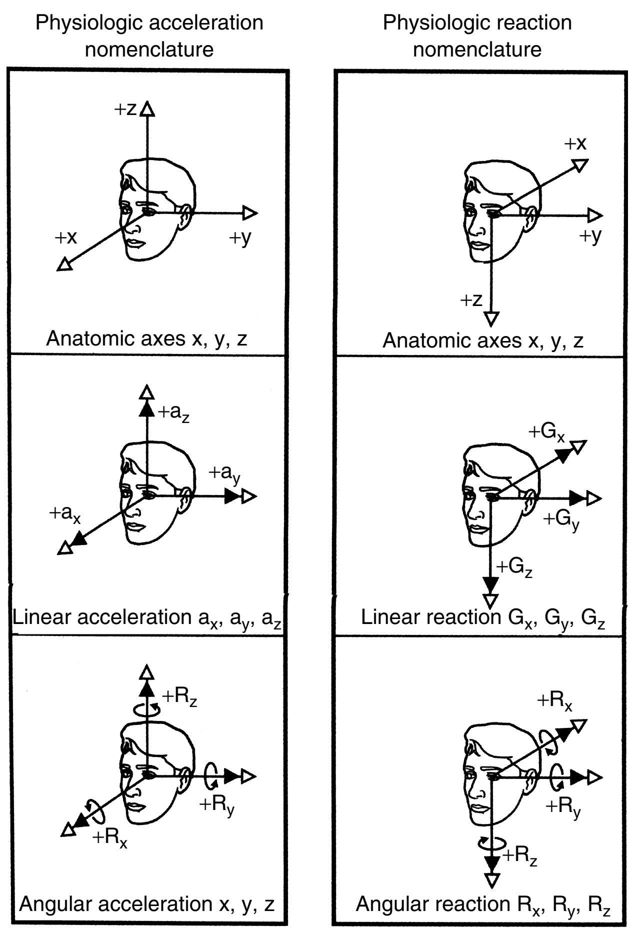


FIGURE 6-2 System for describing accelerations and inertial reactions in humans. (Adapted from Hixson WC, Niven JI, Correia MJ. Kinematics nomenclature for physiological accelerations, with special reference to vestibular applications. Monograph 14. Pensacola, Florida: Naval Aerospace Medical Institute, 1966.)

of the positive directions of a_x, a_y, and a_z accelerations in this particular system: if one lets the forward-pointing index finger of the right hand represent the positive x-axis and the left-pointing middle finger of the right hand represent the positive y-axis, the positive z-axis is represented by the upward-pointing thumb of the right hand. A different right-hand rule, however, is used in another convention, one for describing vehicular coordinates. In that system, $+a_x$ is noseward acceleration, $+a_y$ is to the right, and $+a_z$ is floorward; an inverted right hand illustrates that set of axes.

The angular accelerations, α_x, α_y, and α_z, are roll, pitch, and yaw accelerations, respectively, in the system shown in Figure 6-2. Note that the relations between the positive x-axis, y-axis, and z-axis are identical to those for linear accelerations. The direction of positive angular displacement, velocity, or acceleration is described by another right-hand rule, wherein the flexed fingers of the right hand indicate the direction of angular motion corresponding to the vector represented by the extended, abducted right thumb. Therefore, in this system, a right roll results from $+\alpha_x$ acceleration, a pitch down results from $+\alpha_y$ acceleration, and a left yaw results from $+\alpha_z$ acceleration. Again, it is important to be aware of the inverted right-hand coordinate system commonly used to describe angular motions of vehicles. In that convention, a positive roll acceleration is to the right, positive pitch is upward, and positive yaw is to the right. Our system describes the motion of the vehicle occupant.

The nomenclature for the direction of gravitoinertial (G) forces acting on humans is also illustrated in Figure 6-2. Note that the relation of these axes to each other follows a backward, inverted, right-hand rule. In the illustration convention, $+\alpha_x$ acceleration results in $+G_x$ inertial force, and $+\alpha_z$ acceleration results in $+G_z$ force. This correspondence of polarity is not achieved on the y-axis, however, because $+a_y$ acceleration results in $-G_y$ force. If the $+G_y$ direction were reversed, full polarity correspondence could be achieved between all linear accelerations and all reactive forces, and that convention has been used by some authors. An example of the usage of the symbolic reaction terminology would be: "An F-16 pilot must be able to sustain $+9.0\ G_z$ without losing vision or consciousness."

The "eyeballs" nomenclature is another useful set of terms for describing gravitoinertial forces. In this system, the direction of the inertia reaction of the eyeballs, when the head is subjected to an acceleration, is used to describe the direction of the inertial force. The equivalent expressions, "eyeballs-in acceleration" and "eyeballs-in G force," leave little room for confusion about either the direction of the applied acceleratory field or the resulting gravitoinertial force environment.

Inertial torques can be described conveniently by means of the system shown in Figure 6-2, in which the angular reaction axes are the same as the linear reaction axes. The inertial reactive torque resulting from $+\alpha_x$ (right roll) angular acceleration is $+R_x$ and $+\alpha_z$ (left yaw) results in $+R_z$; however, $+\alpha_y$ (downward pitch) results in $-R_y$. This incomplete correspondence between acceleration and reaction coordinate polarities again results from the mathematical tradition of using right-handed coordinate systems.

It should be apparent from all this that the potential for confusing the audience when speaking or writing about acceleration and inertial reaction is great enough to make it a virtual necessity to describe the coordinate system being used. For most applications, the "eyeballs" convention is perfectly adequate.

VISUAL ORIENTATION

Vision is by far the most important sensory modality subserving spatial orientation, especially so in moving vehicles such as aircraft. Without it, flight as we know it would be impossible, whereas this would not be necessarily the case in the absence of the vestibular or other sensory systems that provide orientation information. Certain special features of visual orientation deserve mention. First, there are two separate visual orientation systems that have two distinct functions: object recognition and spatial orientation. Knowledge of these systems is extremely important to help in understanding visual illusions in flight and appreciate the difficulties inherent in using flight instruments for spatial orientation. Second, visual and vestibular orientation information is integrated at very basic neural levels. For that reason, SD is frequently not amenable to correction by higher-level neural processing.

Anatomy and the Visual System

General

The retina, an evaginated portion of the embryonic brain, consists of an outer layer of pigmented epithelium and an inner layer of neural tissue. Contained within the latter layer are the sensory rod and cone cells, the bipolar and horizontal cells that comprise the intraretinal afferent pathway from the rods and cones, and the multipolar ganglion cells, the axons of which are the fibers of the optic nerve. The cones, which number approximately 7 million in the human eye, have a relatively high threshold to light energy. They are responsible for sharp visual discrimination and color vision. The rods, of which there are more than 100 million, are much more sensitive to light than the cones; they produce the ability to see in twilight and at night. In the macula, near the posterior pole of the eye, the cone population achieves its greatest density; within the central macula, the fovea centralis—a small pit totally comprises tightly packed slender cones—provides the sharpest visual acuity and is the anatomic basis for foveal, or central, vision. The remainder of the eye is capable of far less visual acuity and subserves paracentral and peripheral vision.

Having dendritic connections with the rods and cones, the bipolar cells provide axons that synapse with the dendrites or cell bodies of the multipolar ganglion cells, whose axons in turn course parallel to the retinal surface and converge at the optic disk. Emerging from the eye as the optic nerve, they meet their counterparts from the opposite eye in the optic chiasm and then continue in one of the optic tracts, most likely to terminate in a lateral geniculate body, but possibly in a superior colliculus or the pretectal area. Second-order neurons from the lateral geniculate body comprise the geniculocalcarine tract, which becomes the optic radiation and terminates in the primary visual cortex, the striate area of the occipital cortex (area 17). In the visual cortex, the retinal image is represented as a more or less point-to-point projection from the lateral geniculate body, which receives a similar topographically structured projection from both retinae. The lateral geniculate and the primary visual cortex are therefore structurally and functionally suited for the recognition and analysis of visual images. The superior colliculi project to the visual association areas (areas 18 and 19) of the cerebral cortex through the pulvinar, and eventually to the motor nuclei of the extraocular muscles and muscles of the neck, and appear to provide a pathway for certain gross ocular reflexes of visual origin. Fibers entering the pretectal area are involved in pupillary reflexes. In addition, most anatomic and physiologic evidence indicates that information from the occipital visual association areas, parietal cerebral cortex, and frontal eye movement area (area 8) is relayed through the paramedian pontine reticular formation to the nuclei of the cranial nerves innervating the extraocular muscles. Through this pathway and perhaps others involving the superior colliculi, saccadic (fast) and pursuit (slow) eye movements are initiated and controlled. Third- and fourth-order neurons are immensely complex with some neurons having more than a thousand synapses per cell, and their projections become diffusely integrated within the entire nervous system.

Visual–Vestibular Convergence

Vision in humans and other primates is highly dependent on cerebral cortical structure and function, whereas vestibular orientation primarily involves more primitive anatomic structures. Yet visual and vestibular orientational processes are by no means independent. We know that visually perceived motion information and probably other visual orientational data reach the vestibular nuclei in the brainstm (4,5), but it appears that a major integration of visual and vestibular orientational information is first accomplished in the cerebral cortex.

The geniculostriate projection system, responsible for conscious visual awareness, is divided both anatomically and functionally into two parts: the parvocellular layers of the lateral geniculate body (the "parvo" system) and the magnocellular layers (the "magno" system). These systems remain partly segregated in the primary visual cortex, undergo further segregation in the visual association cortex, and ultimately terminate in the temporal and parietal lobes, respectively. The parvo system neurons have smaller, more centrally located receptive fields that exhibit high spatial resolution (acuity), and they respond well to color; they do not, however, respond well to rapid motion or high flicker rates. The magno cells, by comparison, have larger receptive fields and respond better to motion and flicker, but are relatively insensitive to color differences. Magno neurons generally exhibit poorer spatial resolution, although they seem to respond better than parvo neurons at low luminance contrasts. In general, the parvo system is better at detecting small, slowly moving, colored targets located near the center of the visual field, whereas the magno system is more capable of processing rapidly moving and optically degraded stimuli across larger regions of the visual field.

What is important about these two components of the geniculostriate system is that the parvo system projects ventrally to the inferior temporal areas, which are involved in visual search, pattern recognition, and visual object memory, whereas the magno system projects dorsally to the posterior parietal and superior temporal areas, which are specialized for motion information processing. The cerebral cortical areas to which the parvo system projects receive virtually no vestibular afferents; the areas to which the magno system projects, on the other hand, receive significant vestibular and other sensory inputs, and are believed to be involved to a greater extent in maintaining spatial orientation.

The posterior parietal region projects heavily to cells of the pontine nuclei, which in turn provide the mossy-fiber visual input to the cerebellar cortex. Through the accessory optic and central tegmental tracts, visual information also reaches the inferior olives, which provide climbing fiber input to the cerebellar cortex. The cerebellar cortex, specifically the flocculonodular lobe and vermis, also receives direct mossy-fiber input from the vestibular system. Therefore, cerebellar cortex is another area of very strong visual–vestibular convergence. Furthermore, the cerebellar Purkinje cells have inhibitory connections in the vestibular nuclei and possibly even in the vestibular end organs; so visual–vestibular interactions mediated by the cerebellum also occur at the level of the brainstem, and maybe even peripherally.

Finally, there is a confluence of visual and vestibular pathways in the paramedian pontine reticular formation. Integration of visual and vestibular information in the cerebellum and brainstem appears to allow visual control of basic equilibratory reflexes of vestibular origin. As might be expected, there are also afferent vestibular influences on visual system nuclei; these influences have been demonstrated in the lateral geniculate body and superior colliculus.

Visual Information Processing

Primary control of the human ability to move and orient ourselves in three-dimensional space is mediated by the visual system, as exemplified by the fact that individuals without functioning vestibular systems (“labyrinthine defectives”) have virtually no problems with spatial orientation unless they are deprived of vision. The underlying mechanisms of visual orientation-information processing are revealed by receptive-field studies, which have been accomplished for the peripheral retina, relay structures, and primary visual cortex. Basically, these studies show that there are several types of movement-detecting neurons and that these neurons respond differently to such features as the direction of movement, velocity of movement, size of the stimulus, its orientation in space, and the level of illumination (6).

As evidenced by the division of the primate geniculostriate system into two separate functional entities, however, vision must be considered as two separate processes. Some researchers emphasize the role of the ventral (parvo) system in object recognition (the “what” system) and that of the dorsal (magno) system in spatial orientation (the “where” system); others categorize the difference in terms of form (occipitotemporal) versus motion (occipitoparietal) processing. A recent theory suggests that the dorsal system is primarily involved in processing information in peripersonal (near) space during reaching and other visuomotor activity, whereas the ventral system is principally engaged in visual scanning in extrapersonal (far) visual space (7). In the present discussion, we shall refer to the systems as the “focal” and “ambient” visual systems, respectively, subserving the focal and ambient modes of visual processing. Certain aspects of yet another visual process, the one responsible for generating eye movements, will also be described.

Focal Vision

Liebowitz and Dichgans (8) have provided a very useful summary of the characteristics of focal vision:

> [The focal visual mode] is concerned with object recognition and identification and in general answers the question of “what.” Focal vision involves relatively fine detail (high spatial frequencies) and is correspondingly best represented in the central visual fields. Information processed by focal vision is ordinarily well represented in consciousness and is critically related to physical parameters such as stimulus energy and refractive error.

Focal vision uses the central 30 degrees or so of the visual field. Although it is not primarily involved with orienting the individual in the environment, it certainly contributes to the internal viewpoint, derived from judgments of distance and depth and those obtained from reading flight instruments. Tredici (9) categorized the visual cues to distance and depth as monocular or binocular. There are eight monocular cues: (a) size constancy, the size of the retinal image in relation to known and comparative sizes of objects; (b) shape constancy, the shape of the retinal image in relation to the known shape of the object (e.g., the foreshortening of the image of a known circle into an ellipsoid shape means one part of the circle is farther away than the other); (c) motion parallax (also called *optical flow*), the relative speed of movement of images across the retina such that when an individual is moving linearly in his or her environment, the retinal images of nearer objects move faster than those of objects farther away; (d) interposition, the partial obstruction from view of more distant objects by nearer ones; (e) gradient of texture, the apparent loss of detail with greater distance; (f) linear perspective, the convergence of parallel lines at a distance; (g) illumination perspective, which results from the tendency to perceive the light source to be above an object and from the association of more deeply shaded parts of an object with being farther from the light source; and (h) aerial perspective, the perception of objects to be more distant when the image is relatively bluish or hazy. There are three binocular cues to depth and distance: (a) stereopsis, the visual appreciation of three-dimensional space that results from the fusion of slightly dissimilar retinal images of an object; (b) vergence, the medial rotation of the eyes and the resulting direction of their gaze along more or less converging lines, depending on whether the viewed object is closer or farther, respectively; and (c) accommodation or focusing of the image by changing the curvature of the lens of the eye. Of all the cues listed, size and shape constancy and motion parallax appear to be most important for deriving distance information in flying because they are available at and well beyond the distances at which binocular cues are useful. Stereopsis can provide orientation information at distances up to only approximately 200 m; it is, however, more important in orientation than vergence and accommodation, which are useless beyond approximately 6 m. With the exceptions of formation flight and in-flight refueling, there are few activities that take place within 6 m of an aircraft.

Ambient Vision

Liebowitz and Dichgans (6) have provided a summary of ambient vision:

> The ambient visual mode subserves spatial localization and orientation and is in general concerned with the question of "where." Ambient vision is mediated by relatively large stimulus patterns so that it typically involves stimulation of the peripheral visual field and relatively coarse detail (low spatial frequencies). Unlike focal vision, ambient vision is not systematically related to either stimulus energy or optical image quality. Rather, provided the stimulus is visible, orientation responses appear to be elicited on an "all or none" basis. . . The conscious concomitant of ambient stimulation is low or frequently completely absent.

Ambient vision, therefore, is primarily involved with orienting the individual in the environment. Furthermore, this function is largely independent of the function of focal vision. This becomes evident in view of the fact that one can fully occupy central vision with the task of reading while simultaneously obtaining sufficient orientation cues with peripheral vision to walk or ride a bicycle. It is also evidenced by the ability of certain patients with cerebral cortical lesions to maintain visual orientation responses although their ability to discriminate objects is lost.

Although we commonly think of ambient vision as dependent on stimulation of the peripheral visual field, it is more accurate to consider ambient vision as involving large areas of the total visual field, which includes the periphery. In other words, ambient vision is not so much location dependent as it is area dependent. Moreover, ambient vision is stimulated much more effectively by large images or groups of images perceived to be at a distance than by those appearing to be close.

The function of ambient vision in orientation can be thought of as two processes, one providing motion cues and the other providing position cues. Large, coherently moving contrasts detected over a large area of the visual field result in vection, that is, a visually induced percept of self-motion. If the moving contrasts revolve relative to the subject, he or she perceives rotational self-motion, or angular vection (also called *circular vection*), which can be in the pitch, roll, yaw, or any intermediate plane. If the moving contrasts enlarge and diverge from a distant point, become smaller and converge in the distance, or otherwise indicate linear motion, the percept of self-motion that results is linear vection, which can also be in any direction. Vection can, of course, be real or illusory, depending on whether actual or merely apparent motion of the subject is occurring. One can appreciate the importance of ambient vision in orientation by recalling the powerful sensations of self-motion generated by certain scenes in wide-screen motion pictures (e.g., flying through the *Valley Marinaris* Canyon on Mars in an IMAX theater or simulating flight in the popular Disney Epcot ride "Soarin.")

Position cues provided by ambient vision are readily evidenced in the stabilization of posture that vision affords patients with defective vestibular or spinal proprioceptive systems. The essential visual parameter contributing to postural stability appears to be the motion of the retinal image that results from minor deviations from desired postural position. Visual effects on posture can also be seen in the phenomenon of height vertigo. As the distance from (height above) a stable visual environment increases, the amount of body sway necessary for the retinal image movement to be above threshold increases. Above a certain height, the ability of this visual mechanism to contribute to postural stability is exceeded and vision indicates posture to be stable despite large body sways. The conflict between visual orientation information, indicating relative stability, and the vestibular and somatosensory data, indicating large body sways, results in the unsettling experience of vertigo.

One more distinction between focal and ambient visual function should be emphasized. In general, focal vision serves to orient the perceived object relative to the individual, whereas ambient vision serves to orient the individual relative to the perceived environment. When both focal and ambient vision are present, orienting a focally perceived object relative to the ambient visual environment is easy, whether the mechanism employed involves first orienting the object to oneself and then orienting oneself and the object to the environment or whether the object is oriented directly to the environment. When only focal vision is available, however, it can be difficult to orient oneself correctly because the natural tendency is to perceive oneself as stable and upright and to perceive the focally viewed object as oriented with respect to the stable and upright egocentric reference frame. This phenomenon can cause a pilot to misjudge the approach to a night landing, for example, when only the runway lights and a few other focal visual cues are available for spatial orientation.

Eye Movements

We distinguish between two fundamental types of eye movement: smooth movements, including pursuit, vergence, and those driven by the vestibular system; and saccadic (jerky) movements. Smooth eye movements are controlled at least in part by the posterior parietal cerebral cortex and surrounding areas, as evidenced by functional deficits resulting from damage to these areas. Eye movements of vestibular origin are primarily generated by very basic reflexes involving brainstem mechanisms; and because visual pursuit eye movements are impaired by vestibular and certain cerebellar lesions, the vestibular system appears to be involved in the control of smooth eye movements even of visual origin. Saccadic eye movements are controlled mainly by the frontal eye fields of the cerebral cortex, which work with the superior colliculus in generating the movements. Frontal eye fields receive their visual input from the cortical visual association areas.

The maintenance of visual orientation in a dynamic motion environment is greatly enhanced by the ability to move the eyes, primarily because the retinal image of the environment can be stabilized by appropriate eye movements. Very powerful and important mechanisms involved in reflexive vestibular stabilization of the retinal image will be discussed in the section **Vestibular Function**. Visual pursuit movements also serve to stabilize the retinal image, as long as the relative motion between the head and the visual environment (or object being observed in it) is less than approximately 60 degrees/s: targets moving at higher relative velocities necessitate either saccadic eye movements or voluntary head movements for adequate tracking. Saccadic eye movements are used voluntarily or reflexively to acquire a target, that is, to move it into focal vision, or to catch up to a target that cannot be maintained on the fovea by pursuit movements. Under some circumstances, pursuit and saccadic eye movements alternate in a pattern of reflexive slow tracking and fast back-tracking called *optokinetic nystagmus*. This type of eye-movement response is typically elicited in the laboratory by surrounding the subject with a rotating striped drum; however, one can exhibit and experience optokinetic nystagmus quite readily in a more natural setting by watching railroad cars go by while waiting at a railroad crossing. Movement of the visual environment sufficient to elicit optokinetic nystagmus provides a stimulus that can either enhance or compete with the vestibular elicitation of eye movements, depending on whether the visually perceived motion is compatible or incompatible, respectively, with the motion sensed by the vestibular system.

Vergence movements, which aid binocular distance and motion perception at very close range, are of relatively minor importance in spatial orientation when compared with the image-stabilizing pursuit and saccadic eye movements. Vergence assumes some degree of importance, however, under conditions where a large visual environment is being simulated in a confined space. Failure to account for vergence effects can result in loss of simulation fidelity: a subject who must converge his or her eyes to fuse an image representing a large, distant object will perceive that object as small and near. To overcome this problem, visual flight simulators display distant scenes at the outer limit of vergence effects (7–10 m) or use lenses or mirrors to put the displayed scene at optical infinity.

Although gross stabilization of the retinal image aids object recognition and spatial orientation by enhancing visual acuity, absolute stability of an image is associated with a marked decrease in visual acuity and form perception. This stability-induced decrement is avoided by continual voluntary and involuntary movements of the eyes, even during fixation of an object. We are unaware of these small eye movements, however, and the visual world appears stable.

Voluntary scanning and tracking movements of the eyes are associated with the appearance of a stable visual environment, but why this is so is not readily apparent. Early investigators postulated that proprioceptive information from extraocular muscles provides not only feedback signals for control of eye movements but also afferent information needed to correlate eye movements with retinal image movements arriving at a subjective determination of a stable visual environment. An alternate mechanism for oculomotor control and subjective appreciation of visual stability is the "corollary discharge" or feed-forward mechanism proposed first by Sperry (10). Sperry concluded, "Thus, an excitation pattern that normally results in a movement that will cause a displacement of the visual image on the retina may have a corollary discharge into the visual centers to compensate for the retinal displacement. This implies an anticipatory adjustment in the visual centers specific for each movement with regard to its direction and speed." The theoretic aspects of visual perception of movement and stability have been expanded over the years into various models based on "inflow" (afference), "outflow" (efference), and even hybrid sensory mechanisms.

In developing the important points on visual orientation, we have emphasized the "focal-ambient" dichotomy. As visual science matures further, this simplistic construct will likely be replaced by more complex models of visual processes. Currently we are enthusiastic about a theory in which the dichotomy emphasized is that between the peripersonal (near) and focal extrapersonal (far) visual realms (5). This theory argues that the dorsal cortical system and its magno projection pathways are more involved in processing visual information from peripersonal space, whereas the ventral system and its parvo projections attend to the focal extrapersonal visual environment. The theory also suggests that visual attention is organized to be employed more efficiently in some sectors of three-dimensional visual space than in others (e.g., far vision is biased toward the upper visual field and utilizes local form processing, whereas near vision is biased toward the lower visual field and is better at global form processing), and that ambient extrapersonal information is largely excluded from attentional mechanisms. Certainly, the current state of knowledge concerning visual orientation is fluid but a good summary is presented by Previc (11).

VESTIBULAR FUNCTION

The role of vestibular function in spatial orientation is not as overt as that of vision, but it is extremely important for three major reasons. First, the vestibular system provides structural and functional substrate for reflexes that serve to stabilize vision when motion of the head and body would otherwise result in blurring of the retinal image. Second, the vestibular system provides orientational information with reference to which skilled and reflexive motor activities are automatically executed. Third, the vestibular system provides, in the absence of vision, a reasonably accurate perception of motion and position, as long as the pattern of stimulation remains within certain naturally occurring bounds. Because a working knowledge of vestibular anatomy and physiology is essential to the understanding of SD in flight, these details will be presented in the following sections.

Vestibular Anatomy

End Organs

The vestibular end organs are smaller than most people realize, measuring just 1.5 cm across and reside in some of the densest bone in the body, the petrous portion of the temporal bone. Each temporal bone contains a tortuous excavation known as the *bony labyrinth*, which is filled with perilymph, a fluid much like cerebrospinal fluid. The bony labyrinth consists of three main parts: the cochlea, the vestibule, and the semicircular canals (Figure 6-3). Within each part of the bony labyrinth is a part of the delicate, tubular, membranous labyrinth, which contains endolymph, a fluid characterized by its relatively high concentration of positive ions. In the cochlea, the membranous labyrinth is called the *cochlea duct* or *scala media*; this organ converts acoustic energy into neural information. In the vestibule lie the two otolith organs, the utricle and the saccule. They translate gravitational and inertial forces into spatial orientation information—specifically, information about the angular position (tilt) and linear motion of the head. They are in effect, linear accelerometers. Semicircular ducts, in the semicircular canals, convert inertial torques into information about angular motion of the head. They function as angular accelerometers. The three semicircular canals and their included semicircular ducts are oriented in three mutually perpendicular planes, thereby inspiring the names of the canals: anterior vertical (or superior), posterior vertical (or posterior), and horizontal (or lateral).

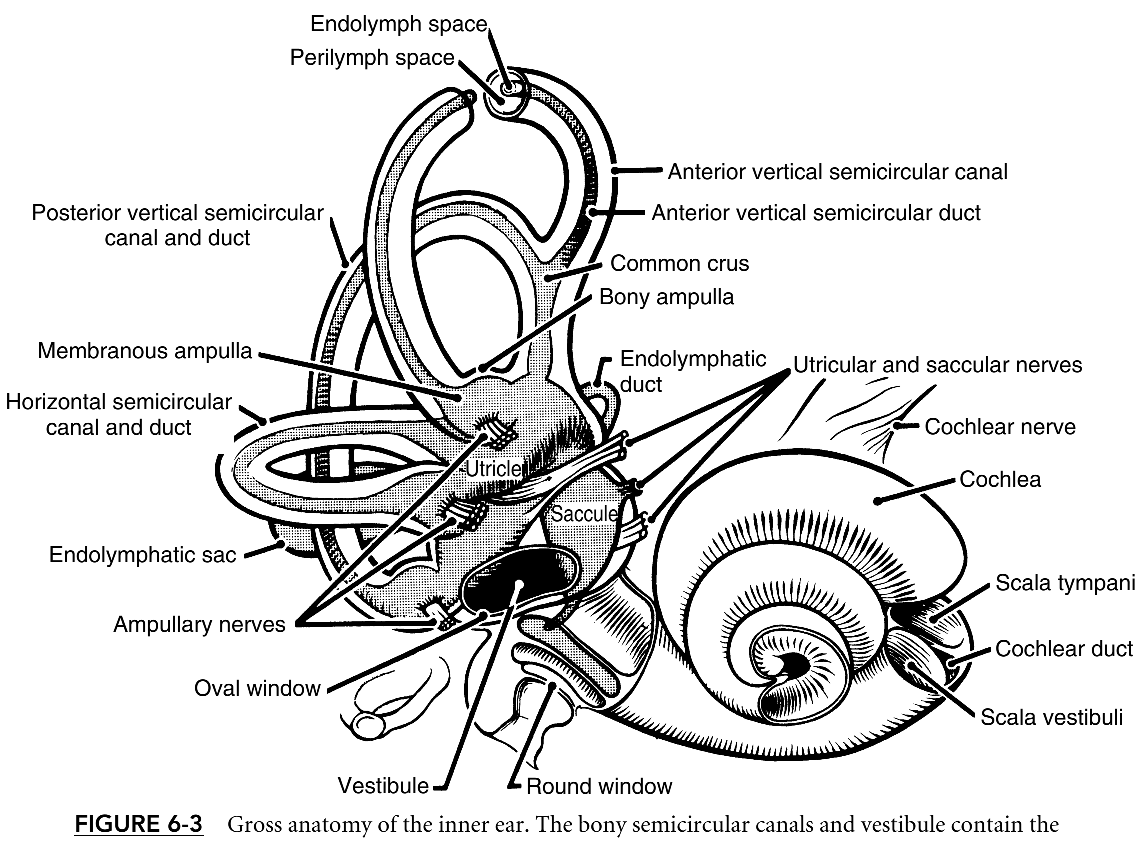


FIGURE 6-3 Gross anatomy of the inner ear. The bony semicircular canals and vestibule contain the membranous semicircular ducts and otolith organs, respectively.

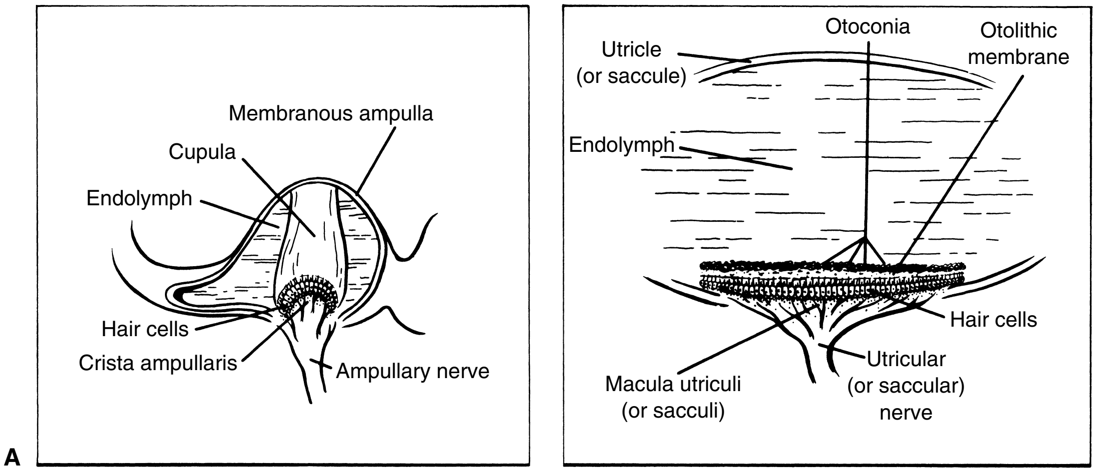


FIGURE 6-4 The vestibular end organs. **A:** The ampulla of the semicircular duct, containing the crista ampullaris and cupula. **B:** A representative otolith organ, with its macula and otolithic membrane.

The semicircular ducts communicate at both ends with the utricle, and one end of each duct is dilated to form an ampulla. Inside each ampulla lies a crest of neuroepithelium, the crista ampullaris. Atop the crista, occluding the duct, is a gelatinous structure called the *cupula* (Figure 6-4A). The hair cells of the crista ampullaris project their cilia into the base of the cupula. When inertial torques of the endolymph ring, in the semicircular duct, deviate the cupula the cilia are bent.

Lining the bottom of the utricle in a more or less horizontal plane is another patch of neuroepithelium, the macula utriculi, and on the medial wall of the saccule in a vertical plane is still another, the macula sacculi (Figure 6-4B). The cilia of the hair cells comprising these structures project into overlying otolithic membranes, one above each macula. The otolithic membranes are gelatinous structures containing many tiny calcium carbonate crystals, called *otoconia*, which are held together by a network of connective tissue. Having approximately three times the density of the surrounding endolymph, the otolithic membranes displace endolymph and shift position relative to their respective maculae when subjected to changing gravitoinertial forces. This shifting of the otolithic membrane position results in bending of the cilia of the macular hair cells.

The hair cell is the functional unit of the vestibular sensory system. It converts spatial and temporal patterns of mechanical energy applied to the head into neural information. Each hair cell possesses one relatively large kinocilium on one side of the top of the cell and up to 100 smaller stereocilia on the same surface, except for the area covered by the large kinocilium. Hair cells therefore exhibit morphologic polarization, that is, they are oriented in a particular direction. The functional correlate of this polarization is when the cilia of a hair cell are bent in the direction of its kinocilium, the cell undergoes an electrical depolarization, and the frequency of action potentials generated in the vestibular neuron attached to the hair cell increases above a certain resting frequency; the greater the deviation of the cilia, the higher the frequency. Similarly, when its cilia are bent away from the side with the kinocilium, the hair cell undergoes an electrical hyperpolarization, and the frequency of action potentials in the corresponding neuron in the vestibular nerve decreases (Figure 6-5).

The same basic process described earlier occurs in all of the hair cells in the three cristae and both maculae; the important differences lie in the physical events that cause the deviation of cilia and in the directions in which the

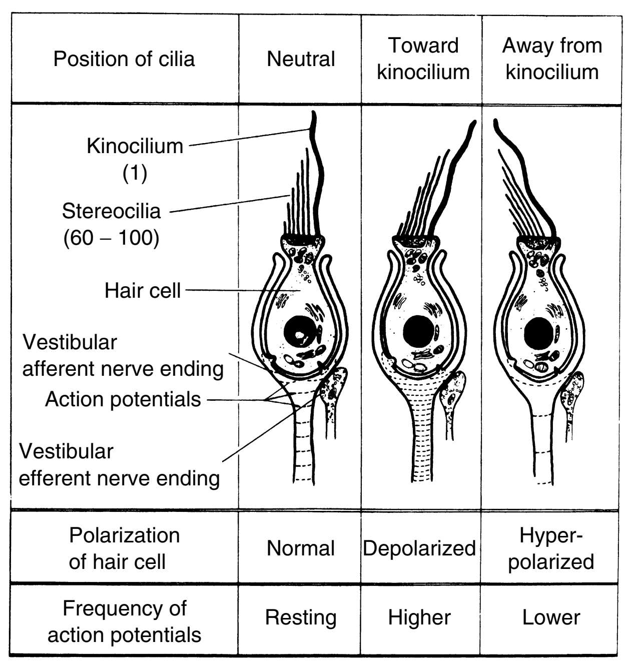


FIGURE 6-5 Function of a vestibular hair cell. When mechanical forces deviate the cilia toward the side of the cell with the kinocilium, the hair cell depolarizes and the frequency of action potentials in the associated afferent vestibular neuron increases. When the cilia are deviated in the opposite direction, the hair cell hyperpolarizes and the frequency of action potentials decreases.

various groups of hair cells are oriented. The hair cells of a crista ampullaris respond to the inertial torque of the ring of endolymph contained in the attached semicircular duct as the reacting endolymph exerts pressure on the cupula causing deviation. The hair cells of a macula, on the other hand, respond to the gravitoinertial force acting to displace the overlying otolithic membrane. As indicated in Figure 6-6A, all of the hair cells in the crista of the horizontal semicircular duct are oriented so that their kinocilia are on the utricular side of the ampulla. Therefore, utriculopetal endolymphatic pressure on the cupula deforms the cilia of these hair cells toward the kinocilia, and all the hair cells in the crista depolarize. The hair cells in the cristae of the vertical semicircular ducts are oriented in the opposite manner, that is, their kinocilia are all on the side away from the utricle. In the ampullae of the vertical semicircular ducts, therefore, utriculopetal endolymphatic pressure deforms the cilia away from the kinocilia, causing all of the hair cells in these cristae to hyperpolarize. In contrast, the hair cells of the maculae are not oriented unidirectionally across the neuroepithelium: the direction of their morphologic polarization depends on where they lie on the macula (Figure 6-6B). In both maculae, there is a central line of reflection, on opposing sides of which the hair cells assume an opposite orientation. In the utricular macula, the kinocilia of the hair cells are all oriented toward the line of reflection, whereas in the saccular macula they are oriented away from it. Because the line of reflection on each macula curves at least 90 degrees, the hair cells, having morphologic polarization roughly perpendicular to this line, assume virtually all possible orientations on the plane of the macula. Therefore, the orthogonality of the planes of the three semicircular ducts enables them to efficiently detect angular motion in any plane, and the perpendicularity of the planes of the maculae plus the omnidirectionality of the orientation of the hair cells in the maculae allow the efficient detection of gravitoinertial forces acting in any direction (12). It remains for the brain to integrate the information gathered by these peripheral sensors.

Neural Pathways

To help the reader better organize the potentially confusing vestibular neuroanatomy, a somewhat simplified overview of the major neural connections of the vestibular system is presented in Figure 6-7. The utricular nerve, two saccular nerves, and the three ampullary nerves converge to form the vestibular nerve, a portion of the VIII cranial vestibulocochlear or acoustic nerve. Within the vestibular nerve lies the vestibular (or Scarpa's) ganglion, which comprises cell bodies of the vestibular neurons. The dendrites of these bipolar neurons invest the hair cells of the cristae and maculae; most of their axons terminate in the four vestibular nuclei in the brainstem—the superior, medial, lateral, and inferior nuclei—but some axons enter the phylogenetically ancient parts of the cerebellum to terminate in the fastigial nuclei and in the cortex of the flocculonodular lobe and other parts of the posterior vermis.

The vestibular nuclei project through secondary vestibular tracts to the motor nuclei of the cranial and spinal nerves

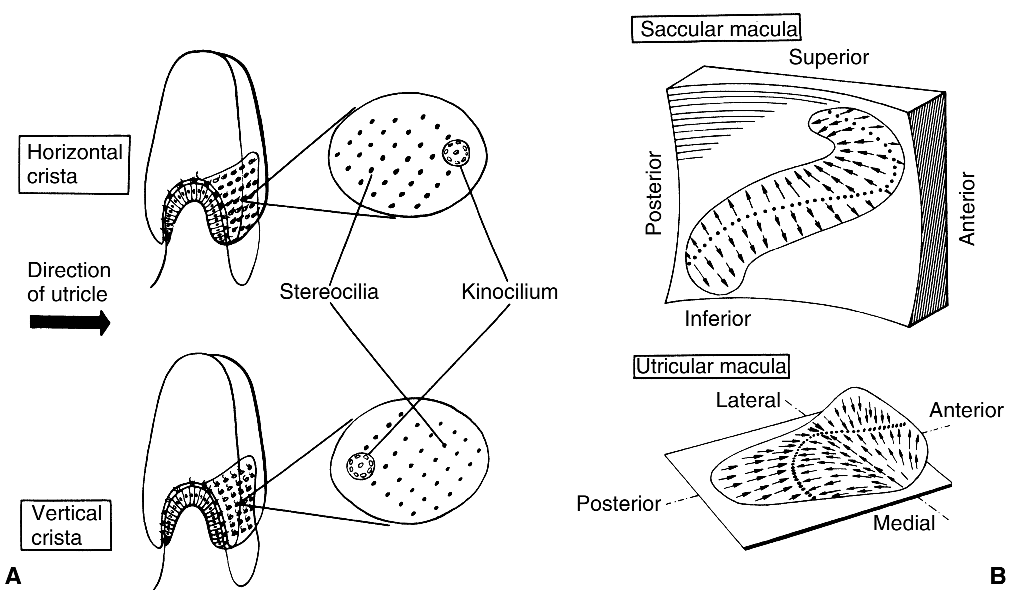


FIGURE 6-6 Morphologic polarization in vestibular neuroepithelia. **A:** All the hair cells in the cristae of the horizontal semicircular ducts are oriented so that their kinocilia are in the direction of the utricle; those hair cells in the cristae of the vertical ducts have their kinocilia directed away from the utricle. **B:** The maculae of the saccule (*above*) and utricle (*below*) also exhibit polarization—the *arrows* indicate the direction of the kinocilia of the hair cells in the various regions of the maculae. (Adapted from Spoendlin HH. Ultrastructural studies of the labyrinth in squirrel monkeys. The role of the vestibular organs in the exploration of space. NASA-SP-77. Washington, DC: National Aeronautics and Space Administration, 1965.)

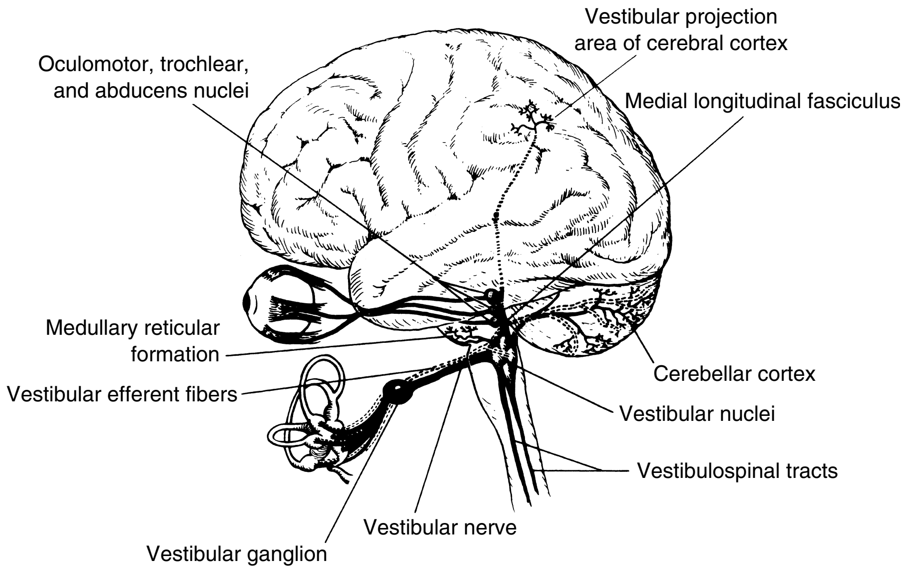


FIGURE 6-7 Major connections and projections of the vestibular system.

and to the cerebellum. Because vestibulo-ocular reflexes are a major function of the vestibular system, it is not surprising to find ample projections from the vestibular nuclei to the nuclei of the oculomotor, trochlear, and abducens nerves (cranial nerves III, IV, and VI, respectively). The major pathway of these projections is the ascending medial longitudinal fasciculus (MLF). The basic vestibulo-ocular reflex is therefore served by sensor and effector cells and an intercalated three-neuron reflex arc from the vestibular ganglion to the vestibular nuclei to the nuclei innervating the extraocular muscles. In addition, indirect multisynaptic pathways course from the vestibular nuclei through the paramedian pontine reticular formation to the oculomotor and other nuclei. The principle of ipsilateral facilitation and contralateral inhibition through an interneuron clearly operates in vestibulo-ocular reflexes, and numerous crossed internuclear connections provide evidence of this. The vestibulo-ocular reflexes that the various ascending and crossed pathways support serve to stabilize the retinal image by moving the eyes in the direction opposite to that of the motion of the head. Through the descending MLF and medial vestibulospinal tract, crossed and uncrossed projections from the vestibular nuclei reach the nuclei of the spinal accessory nerve (cranial nerve XI) and motor nuclei in the cervical cord. These projections form the anatomic substrate for vestibulocollic reflexes, which serve to stabilize the head by appropriate action of the sternocleidomastoid and other neck muscles. A third projection is that from primarily the lateral vestibular nucleus into the ventral gray matter throughout the length of the spinal cord. This important pathway is the uncrossed lateral vestibulospinal tract, which enables the vestibulospinal (postural) reflexes to help stabilize the body with respect to an inertial frame of reference by means of sustained and transient vestibular influences on basic spinal reflexes. Secondary vestibulocerebellar fibers course from the vestibular nuclei into the ipsilateral and contralateral fastigial nuclei and to the cerebellar cortex of the flocculonodular lobe and elsewhere. Returning from the fastigial and other cerebellar nuclei, crossed and uncrossed fibers of the cerebellobulbar tract terminate in the vestibular nuclei and in the associated reticular formation. There are also efferent fibers from the cerebellum, probably arising in the cerebellar cortex, which terminate not in nuclear structures but on dendritic endings of primary vestibular afferent neurons in the vestibular neuroepithelia. Such fibers are those of the vestibular efferent system, which appears to modulate or control the information arising from the vestibular end organs. This creates plasticity in the system, allowing for adaptation. This becomes very important in the environment of flight with "excess" acceleration, or in space, with a "deficit" of acceleration. The primary and secondary vestibulocerebellar fibers and those returning from the cerebellum to the vestibular area of the brainstem comprise the juxtarestiform body of the inferior cerebellar peduncle. This structure, along with the vestibular end organs, nuclei, and projection areas in the cerebellum, collectively constitute the so-called vestibulocerebellar axis, the neural complex responsible for processing primary spatial orientation information and initiating adaptive and protective behavior based on that information and integrating all sources of environmental orientation information.

Several additional projections, more obvious functionally than anatomically, are those to certain autonomic nuclei of the brainstem and to the cerebral cortex. The dorsal motor nucleus of cranial nerve X (vagus) and other autonomic cell groups in the medulla and pons receive secondary vestibular fibers, largely from the medial vestibular nucleus; these fibers mediate vestibulovegetative reflexes, which are manifested during motion sickness as pallor, perspiration, nausea, and vomiting that can result from excessive or otherwise abnormal vestibular stimulation. Through vestibulothalamic and thalamocortical pathways, vestibular information eventually reaches the primary vestibular projection area of the cerebral cortex, located in the parietal and parietotemporal cortex. This projection area is provided with vestibular, visual, and somatosensory proprioceptive representation and is evidently associated with conscious spatial orientation and with integration of sensory correlates of higher-order motor activity. In addition, vestibular information can be transmitted through long polysynaptic pathways through the brainstem reticular formation and medial thalamus to wide areas of the cerebral cortex; the nonspecific cortical responses to vestibular stimuli that are evoked through this pathway appear to be associated with an arousal or alerting mechanism.

Vestibular Information Processing

While reading the discussion of the anatomy of the vestibular end organs, the reader probably deduced that angular accelerations are adequate physiologic stimuli for the semicircular ducts, and linear accelerations and gravity are adequate stimuli for the otolith organs. This statement, illustrated in Figure 6-8, is the cardinal principle of vestibular mechanics. How the reactive torques and gravitoinertial forces stimulate the hair cells of the cristae and maculae, respectively, and produce changes in the frequency of action potentials in the associated vestibular neurons has already been discussed. The resulting frequency-coded messages are transmitted into the various central vestibular projection areas as raw orientational data to be further processed as necessary for the various functions served by such data. These functions are the vestibular reflexes, voluntary movement, and the perception of orientation.

Vestibular Reflexes

As stated so well by Melvill Jones (13), "... for control of eye movement relative to space the motor outflow can operate on three fairly discrete anatomical platforms, namely: (1) the eye-in-skull platform, driven by the external eye muscles, rotating the eyeball relative to the skull; (2) the skull-on-body platform driven by the neck muscles; and (3) the body platform, operated by the complex neuromuscular mechanisms responsible for postural control."

In humans, the retinal image is stabilized mainly by vestibulo-ocular reflexes, primarily those of semicircular-duct origin. A simple demonstration can help one appreciate the contribution of the vestibulo-ocular reflexes to retinal-image stabilization. Holding the extended fingers half a meter or so in front of the face, one can move the fingers slowly from side to side and still see them clearly because of visual (optokinetic) tracking reflexes. As the frequency of movement increases, one eventually reaches a point where the fingers cannot be seen clearly—they are blurred by the movement. This point is approximately 60 degrees/s or 1 or 2 Hz for most people. Now, if the fingers are held still and the head is rotated back and forth at the frequency at which the fingers became blurred when they were moved, the fingers remain perfectly clear. Even at considerably higher frequencies of head movement, the vestibulo-ocular reflexes initiated by the resulting stimulation of the semicircular ducts function to keep the image of the fingers clear. Therefore, at lower frequencies of movement of the external world relative to the body or vice versa, the visual system stabilizes the retinal image by means of optokinetic reflexes. As the frequencies of such relative movement become greater, however, the vestibular system, by means of vestibulo-ocular reflexes, assumes progressively more of this function, and at the higher frequencies of relative motion characteristically generated only by motions of the head and body, the vestibular system is responsible for stabilizing the retinal image.

The mechanism by which stimulation of the semicircular ducts results in retinal image stabilization is simple, at least conceptually (Figure 6-9). When the head is turned to the right in the horizontal (yaw) plane, the angular acceleration of the head creates a reactive torque in the ring of endolymph of the horizontal semicircular duct. The reacting endolymph

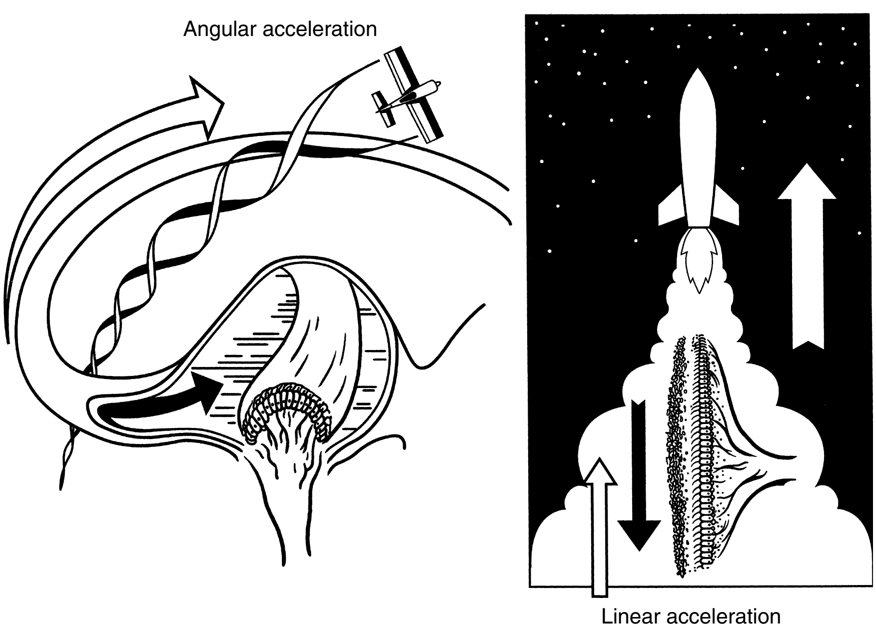


FIGURE 6-8 The cardinal principle of vestibular mechanics: angular accelerations stimulate the semicircular ducts; linear accelerations and gravity stimulate the otolith organ.

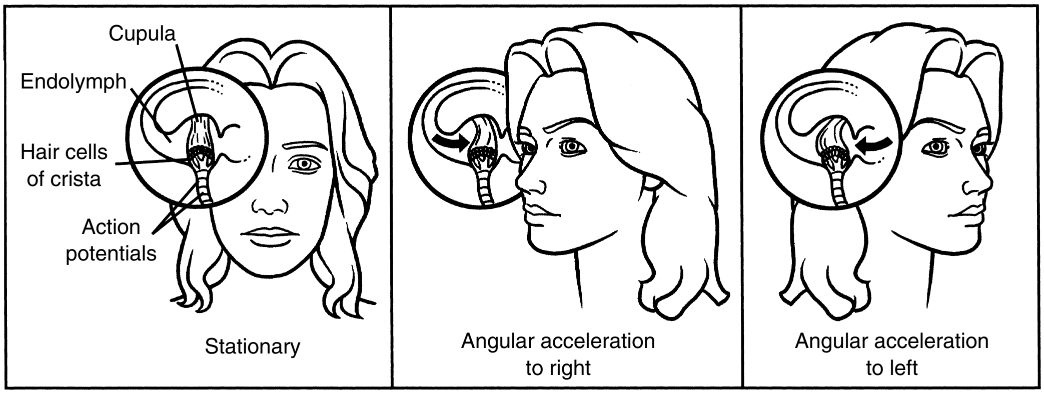


FIGURE 6-9 Mechanism of action of a horizontal semicircular duct and the resulting reflex eye movement. Angular acceleration to the right increases the frequency of action potentials originating in the right ampullary nerve and decreases in those of the left one. This pattern of neural signals causes extraocular muscles to rotate the eyes in the direction opposite to that of head rotation, thereby stabilizing the retinal image with a compensatory eye movement. Angular acceleration to the left has the opposite effect.

then exerts pressure on the cupula, deviating the cupula in the right ear in an utriculopetal direction, depolarizing the hair cells of the associated crista ampullaris and increasing the frequency of the action potentials in the corresponding ampullary nerve. In the left ear, the endolymph deviates the cupula in an utriculofugal direction, thereby hyperpolarizing the hair cells and decreasing the frequency of the action potentials generated. As excitatory neural signals are relayed to the contralateral lateral rectus and ipsilateral medial rectus muscles, and inhibitory signals are simultaneously relayed to the antagonists, a conjugate deviation of the eyes results from the described changes in ampullary neural activity. The direction of the conjugate eye deviation is the same as that of the angular reaction of the endolymph, and the angular velocity of the deviation is proportional to the pressure exerted by the endolymph on the cupula. Therefore, the resulting eye movement is compensatory, adjusting the angular position of the eye to compensate for changes in angular position of the head and thereby preventing slippage of the retinal image over the retina. Because the amount of angular deviation of the eye is physically limited, rapid movements of the eye in the direction opposite to the compensatory motion are employed to return the eye to its initial position or to advance it to a position from which it can sustain a compensatory sweep for a suitable length of time. These rapid eye movements are anticompensatory, and because of their very high angular velocity, motion is not perceived during this phase of the vestibulo-ocular reflex.

With rapid, high-frequency rotations of the head, the rotational inertia of the endolymph acts to deviate the cupula as the angular velocity of the head builds, and the angular momentum gained by the endolymph during the brief acceleration acts to drive the cupula back to its resting position when the head decelerates to a stop. The cupula-endolymph system thereby functions as an integrating angular accelerometer, that is, it converts angular acceleration data into a neural signal proportional to the angular velocity of the head. This is true for angular accelerations occurring at frequencies normally encountered in terrestrial activities. When angular accelerations outside the dynamic response range of the cupula-endolymph system are experienced, the system no longer provides accurate angular velocity information. When angular accelerations are relatively sustained or when the cupula is kept in a deviated position by other means, such as caloric testing (water 7°C above or below body temperature is instilled into the external auditory canal, adjacent to the horizontal semicircular canal, and thermal convection in the endolymph is generated), the compensatory and anticompensatory phases of the vestibulo-ocular reflex are repeated, resulting in beats of ocular nystagmus (Figure 6-10). The compensatory phase of the vestibulo-ocular reflex is then called the *slow phase*

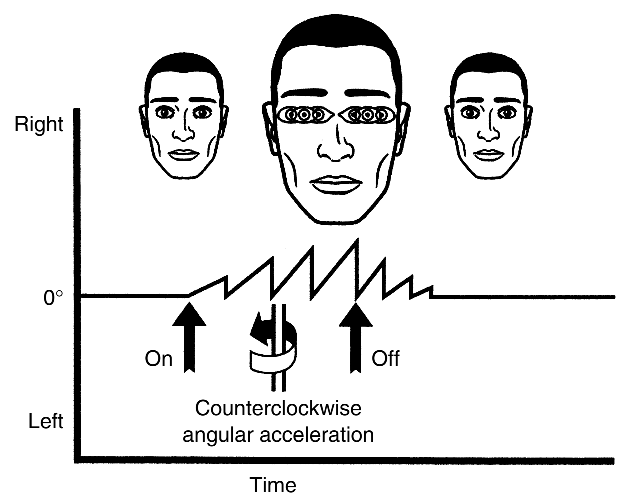


FIGURE 6-10 Ocular nystagmus-repeating compensatory and anticompensatory eye movements resulting from vestibular stimulation. In this case, the stimulation is a yawing angular acceleration to the left, and the anticompensatory, or quick phase, nystagmic response is also to the left.

of nystagmus, and the anticompensatory phase is called the *fast* or *quick phase*. The direction of the quick phase is used to label the direction of the nystagmus because the direction of the rapid motion of the eye is easier to determine clinically. The vertical semicircular ducts operate in an analogous manner, with the vestibulo-ocular reflexes elicited by their stimulation being appropriate to the plane of the angular acceleration resulting in that stimulation. Therefore, a vestibulo-ocular reflex with downward compensatory and upward anticompensatory phases results from the stimulation of the vertical semicircular ducts by pitch-up ($-\alpha_y$) angular acceleration and with sufficient stimulation in this plane, upbeating vertical nystagmus results. Angular accelerations in the roll plane result in vestibulo-ocular reflexes with clockwise and counterclockwise compensatory and anticompensatory phases and in rotary nystagmus. Other planes of stimulation are associated with other directions of eye movement such as oblique or horizontorotary.

As should be expected, there also are vestibulo-ocular reflexes of otolith-organ origin. Initiating these reflexes are the shearing actions that bend the cilia of macular hair cells as inertial forces or gravity cause the otolithic membranes to slide to various positions over their maculae (Figure 6-11). Each position that can be assumed by an otolithic membrane relative to its macula evokes a particular spatial pattern of frequencies of action potentials in the corresponding utricular or saccular nerve, and that pattern is associated with a particular set of compatible stimulus such as backward tilt of the head or forward linear acceleration. These patterns of action potentials from the various otolith organs are correlated and integrated in the vestibular nuclei and cerebellum with orientational information from the semicircular ducts and other sensory modalities; appropriate orientational percepts and motor activities eventually result. Lateral (a_y) linear accelerations can elicit horizontal reflexive eye movements, including nystagmus, presumably as a result of utricular stimulation. Similarly, vertical (a_z) linear accelerations can elicit vertical eye movements, most likely as a result of stimulation of the saccule; the term *elevator reflex* is sometimes used to describe this response because it is readily provoked by the vertical linear accelerations associated with riding in an elevator. The utility of these horizontal and vertical vestibulo-ocular reflexes of the otolith-organ origin is readily apparent: like the reflexes of semicircular-duct origin, they help stabilize the retinal image. Less obvious is the usefulness of the ocular countertorsion reflex (Figure 6-12), which repositions the eyes about the visual (anteroposterior) axes in response to

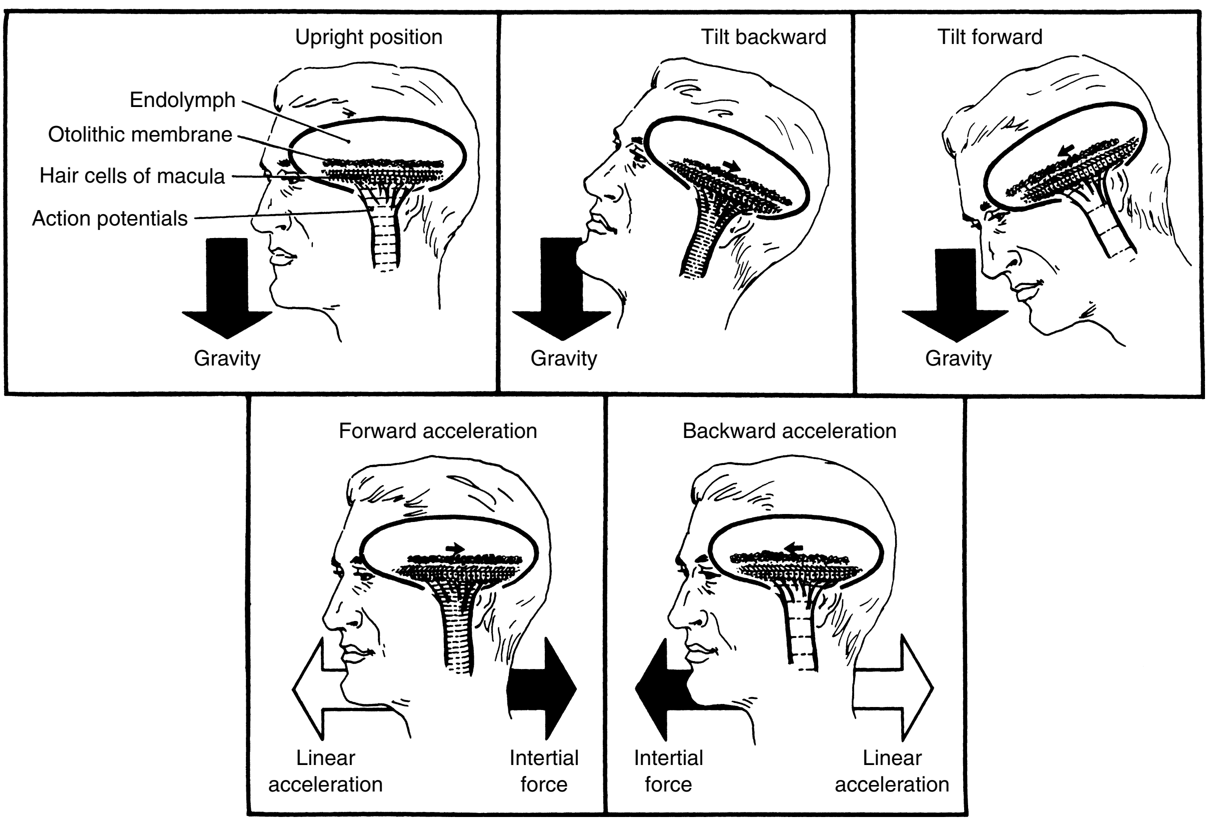


FIGURE 6-11 Mechanism of action of an otolith organ. A change in direction of the force of gravity (*above*) or a linear acceleration (*below*) causes the otolithic membrane to shift its position with respect to its macula, thereby generating a new pattern of action potentials in the utricular or saccular nerve. Shifting of the otolithic membranes can elicit compensatory vestibulo-ocular reflexes and nystagmus, as well as perceptual effects.

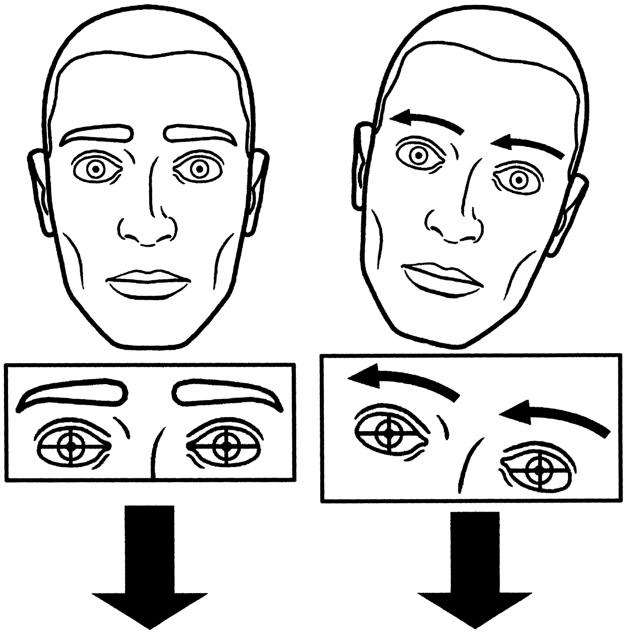


FIGURE 6-12 Ocular countertorsion, a vestibulo-ocular reflex of otolith-organ origin. When the head is tilted to the left, the eyes rotate to the right to assume a new angular position about the visual axes, as shown.

otolith-organ stimulation resulting from tilting the head laterally in the opposite direction. Presumably, this reflex contributes to retinal image stabilization by providing a response to changing directions of the force of gravity.

Our understanding of the vestibulocollic reflexes has not developed to the same degree as that of the vestibulo-ocular reflexes, although measurements of head rotation in response to vestibular stimulation have been used clinically. Perhaps this situation reflects the fact that vestibulocollic reflexes are not as effective as the vestibulo-ocular reflexes in stabilizing the retinal image, at least not in humans. Such is not the case in other species; birds exhibit extremely effective reflex control of head position under conditions of bodily motion. The high level of development of the vestibulocollic reflexes in birds is either a case or a consequence of the relative immobility of birds' eyes in their heads. Nonetheless, the ability of a human (or any other vertebrate with a mobile head) to keep the head upright with respect to the direction of applied gravitoinertial force is maintained by means of tonic vestibular influences on the muscles of the neck.

Vestibulospinal reflexes operate to assure stability of the body. Transient linear and angular accelerations, such as those experienced in tripping and falling, provoke rapid activation of various groups of extensor and flexor muscles to return the body to the stable position or at least to minimize the ultimate effect of the instability. Everyone has experienced the reflexive arm movements that serve to break a fall, and most have observed the more highly developed righting reflexes that cats exhibit when dropped from an upside-down position; these are examples of vestibulospinal reflexes. Less spectacular, but nevertheless extremely important, are the sustained vestibular influences on posture that are exerted through tonic activation of so-called antigravity muscles such as hip, knee, and calf extensors. These vestibular reflexes, of course, help keep the body upright with respect to the direction of the force of gravity.

Voluntary Movement

It is known that the various reflexes of vestibular origin serve to stabilize the body in general and the retinal image in particular. The vestibular system is also important in that it provides data for the proper execution of voluntary movement. To realize just how important such vestibular data are in this context, one must first recognize the fact that skilled voluntary movements are ballistic. Once initiated, the movements are executed according to a predetermined pattern and sequence without the benefit of simultaneous sensory feedback to the higher neural levels from which they originate. The simple act of writing one's signature, for example, involves such rapid changes in speed and direction of movement that conscious sensory feedback and adjustment of motor activity are virtually precluded, at least until the act is nearly completed, at which time the precognitive process becomes recognizable. Learning an element of a skill therefore involves developing a computer-program-like schedule of neural activations that can be called up to effect a particular desired end product of motor activity. Of course, the raw program for a particular voluntary action is not sufficient to permit the execution of that action. Information regarding such parameters as intended magnitude and direction of movement must be furnished from the conscious sphere, and data indicating the position and motion of the body platform relative to the surface of the Earth must be furnished from the preconscious sphere. The necessity for the additional information can be seen in the signature-writing example cited earlier: one can write large or small, quickly or slowly, and on a horizontal or vertical surface. Obviously, different patterns or neuromuscular activation, even grossly different muscle groups, are needed to accomplish a basic act under varying spatial and temporal conditions. The necessary adjustments are made automatically, however, without conscious intervention. Vestibular and other sensory data providing spatial orientation information for use in either skilled voluntary- or reflexive-motor activities are processed into a preconscious orientational percept that provides the informational basis on which such automatic adjustments are made. Therefore one can decide what the outcome of his or her action is to be and initiate the command to do it without consciously having to discern the direction of the force of gravity, analyze its potential effects on planned motor activity, select appropriate muscle groups and modes of activation to compensate for gravity, and then activate and deactivate each muscle in proper sequence and with proper timing to accomplish the desired motor activity. The body takes care of the details, using stored programs for elements of skilled motor activity, and the current preconscious orientational percept. This whole process is the major function and responsibility of the vestibulocerebellar axis.

Conscious Percepts

Usually as a result of the same information processing that provides the preconscious orientational percept, one is also provided a conscious orientational percept. This perception can be false, in which case the individual is said to experience an orientational illusion or to have SD. Moreover, one can be aware that what the body is signaling is not what the mind has concluded from the other orientational information, such as flight instrument data. Conscious orientational percepts can therefore be either natural or derived, depending on the source of the orientation information and the perceptual process involved, and an individual can experience both natural and derived conscious orientational percepts at the same time. Because of this, pilots who have become disoriented in flight commonly exhibit vacillating control inputs, as they alternate indecisively between responding first to one percept and then to the other.

Thresholds of Vestibular Perception

Often, an orientational illusion occurs because the physical event resulting in or from a change in bodily orientation is below the threshold of perception. For example, a person seated in a rotating restaurant perched atop a tower, such as the Seattle Space Needle, cannot sense the rotation of the room. The restaurant completes a 360-degree rotation in 1 hour, therefore its motion is 0.1 degrees/s. The student of disorientation should be aware of the approximate perceptual thresholds associated with the various modes of vestibular stimulation. These thresholds were first described in 1875 by Ernst Mach with considerable accuracy after observing passengers on the great Ferris wheel in Vienna (14). Mach's observations of relationships of the observer to perception would greatly influence Albert Einstein's theory of relativity a few years later (15).

The lowest reported threshold for perception of rotation is 0.035 degrees/s^2, but this degree of sensitivity is obtained only with virtually continuous angular acceleration and long response latencies (20–40 seconds). Other observations put the perceptual threshold between roughly 0.1 and 2.0 degrees/s^2; reasonable values are 0.14, 0.5, and 0.5 degrees/s^2 for yaw, roll, and pitch motions, respectively. It is common practice, however, to describe the thresholds of the semicircular ducts in terms of the angular acceleration-time product, or angular velocity, which results in just perceptible rotation. This product, known as *Mulder's constant*, remains fairly constant for stimulus times of approximately 5 seconds or less. Using the reasonable value of 2 degrees/s for Mulder's constant, an angular acceleration of 5 degrees/s^2 applied for half a second would be perceived because the acceleration-time product is above the 2-degree/s angular velocity threshold. But a 10-degree/s^2 acceleration applied for a 10th of a second would not be perceived because it would be below the angular velocity threshold, nor would a 0.2-degree/s^2 acceleration applied for 5 seconds be perceived. In-flight experiments have shown that blindfolded pilot subjects are unable to perceive consistent roll rates of 1.0 degree/s or less, but can perceive a roll when the velocity is 2.0 degrees/s or higher. Pitch rate thresholds in flight are also between 1.0 and 2.0 degrees/s. However, when aircraft pitch motions are coupled with compensatory power adjustments to keep the net G force always directed toward the aircraft floor, the pitch threshold is raised well above 2.0 degrees/s (10).

The perceptual threshold related to otolith-organ function involves both angle and magnitude because the otolith organs respond to linear accelerations and gravitoinertial forces, both of which have direction and intensity. A 1.5-degree change in direction of applied G force is perceptible under ideal (experimental) conditions. The minimum perceptible intensity of linear acceleration has been reported by various authors to be between 0.001 and 0.03 g, depending on the direction of acceleration and the experimental method used. Values of 0.01 g for a_z and 0.006 g for a_x accelerations are appropriate representative thresholds, and a similar value for a_y acceleration is probably reasonable. Again, these absolute thresholds apply when acceleration is either sustained or applied at relatively low frequencies. The threshold for linear accelerations applied for less than approximately 5 seconds is a constant acceleration-time product, or linear velocity, of approximately 0.3 to 0.4 m/s.

Unfortunately for those who would like to calculate the exact orientational percepts resulting from a particular set of linear and angular accelerations, like those which might have occurred before an aircraft mishap, the actual vestibular perceptual thresholds may vary significantly (16).

The most common reason for an orientational perceptual threshold to be raised is inattention to orientational cues because attention is directed to something else. Other reasons might be a low state of mental arousal, fatigue, drug effects, or innate individual variation. Therefore, it appears that a given individual can monitor his or her own orientation with considerable sensitivity under some circumstances and with relative insensitivity under others. This inconsistency can lead to perceptual errors that result in orientational illusions.

Components of the vestibular system have characteristic frequency responses and stimulation by patterns of acceleration outside the optimal, or "design," frequency-response ranges of the semicircular ducts and otolith organs causes the vestibular system to make errors and generate orientational illusions. The existence of absolute vestibular thresholds and the fact that vestibular thresholds are time varying do not influence the generation of orientational illusions. In flight, much of the stimulation resulting from the acceleratory environment is indeed outside of the design frequency-response ranges of the vestibular end organs; consequently, orientational illusions occur in flight. Elucidation of this important point is provided in the section **Spatial Disorientation**.

Vestibular Suppression and Enhancement

Like all sensory systems, the vestibular system exhibits a decreased response to stimuli that are persistent (adaptation) or repetitious (habituation). Even more important to the aviator is the fact that with time and practice, one can develop the ability to suppress natural vestibular responses, both perceptual and motor. This ability is termed *vestibular suppression*. Closely related to the concept of vestibular suppression is that of visual dominance, the ability to obtain and use spatial orientation cues from the visual environment despite the presence of potentially strong vestibular cues. Importantly, vestibular suppression seems to be exerted through visual dominance because it disappears in the absence of vision. The opposite effect, an increase in perceptual and motor responsiveness to vestibular stimulation, is termed *vestibular enhancement*. Such enhancement can occur when the stimulation is novel, as in an amusement park ride or an aircraft spinning out of control. The first time is always the most sensational.

There is some evidence attributing the function of controlling gain of the vestibular system to the efferent vestibular neurons so as to effect suppression and enhancement. The actual mechanisms involved appear to be much more complex than would be necessary to merely provide gross changes in the gain of the vestibular end organs. Precise control of vestibular responses to anticipated stimulation, based on sensory efferent copies of voluntary commands for movement, is probably exercised by the cerebellum through a feed-forward loop involving the vestibular efferent system. Therefore, when discrepancies between anticipated and actual stimulation generate a neural error signal, a response is evoked and vestibular reflexes and heightened perception occur.

Therefore, vestibular suppression involves the development of accurate estimates of vestibular responses to orientational stimuli repeatedly experienced and the active countering of anticipated responses by spatially and temporally patterned sensory efferent activity. Vestibular enhancement, on the other hand, results from the lack of available estimates of vestibular responses because of the novelty of the stimulation, or perhaps from a revision in neural processing strategy obligated by the failure of normal negative feed-forward mechanisms to provide adequate orientation information. Such marvelous complexity of vestibular function assures adaptability to a wide variety of motional environments and thereby promotes survival in them.

OTHER SENSES OF MOTION AND POSITION

Although the visual and vestibular systems play a dominant role in spatial orientation, the contributions of other sensory systems to orientation cannot be overlooked. Especially important are the nonvestibular proprioceptors: the muscle, tendon, and joint receptors and the cutaneous exteroceptors. This is because the orientational percepts derived from the function of these proprioceptors during flight generally support those derived from vestibular information processing, whether accurate or inaccurate. The utility of these other sensory modalities can be appreciated in view of the fact that in the absence of vision our vestibular, muscle, tendon, joint, and skin receptors allow us to maintain spatial orientation and postural equilibrium to a great extent, at least on the Earth's surface. Similarly, in the absence of vestibular function, vision and the remaining proprioceptors and cutaneous mechanoreceptors are sufficient for appropriate orientation and balance. When two components of this triad of orientational senses are absent or substantially compromised, however, it becomes impossible to maintain sufficient spatial orientation to permit postural stability and effective locomotion, at least until adaptation has occurred.

Nonvestibular Proprioceptors

Sherrington's "proprioceptive" or "self-sensing" sensory category includes the vestibular (or labyrinthine), muscle, tendon, and joint senses. However, proprioception is generally spoken of as though it means only the nonvestibular components.

Muscle and Tendon Senses

Within skeletal muscle there are complex sensory end organs, called *muscle spindles* (Figure 6-13A). These end organs are comprised mainly of small intrafusal muscle fibers that lie parallel to the larger extrafusal muscle fibers and are partially enclosed by a fluid-filled bag (17,18).

The sensory innervation of these structures consists mainly of large, rapidly conducting afferent neurons that originate as primary (annulospiral) or secondary (flower-spray) endings on the intrafusal fibers and terminate in the spinal cord on anterior horn cells and interneurons. Stretching of extrafusal muscle results in an increase in the frequency of action potentials in the afferent nerve from the intrafusal fibers; contraction of the muscle results in a decrease or absence of action potentials. The more interesting aspect of muscle spindle function, however, is that the intrafusal muscle fibers are innervated by motoneurons (γ efferents and others) and can be stimulated to contract, thereby altering the afferent information arising from the spindle. Therefore, the sensory input from the muscle spindles can be biased by descending influences from higher neural centers such as the vestibulocerebellar axis.

Although the muscle spindles are structurally and functionally in parallel with associated muscle groups and respond to changes in their length, the Golgi tendon organs (Figure 6-13B) are functionally in series with the muscles and respond to changes in tension. A tendon organ consists of a fusiform bundle of small tendon fascicles with intertwining neural elements, and is located at the musculotendon junctions or wholly within the tendon. Unlike that of the muscle spindle, its innervation is entirely afferent.

The major function of both the muscle spindles and the tendon organs is to provide the sensory basis for myotatic (or muscle stretch) reflexes. These elementary

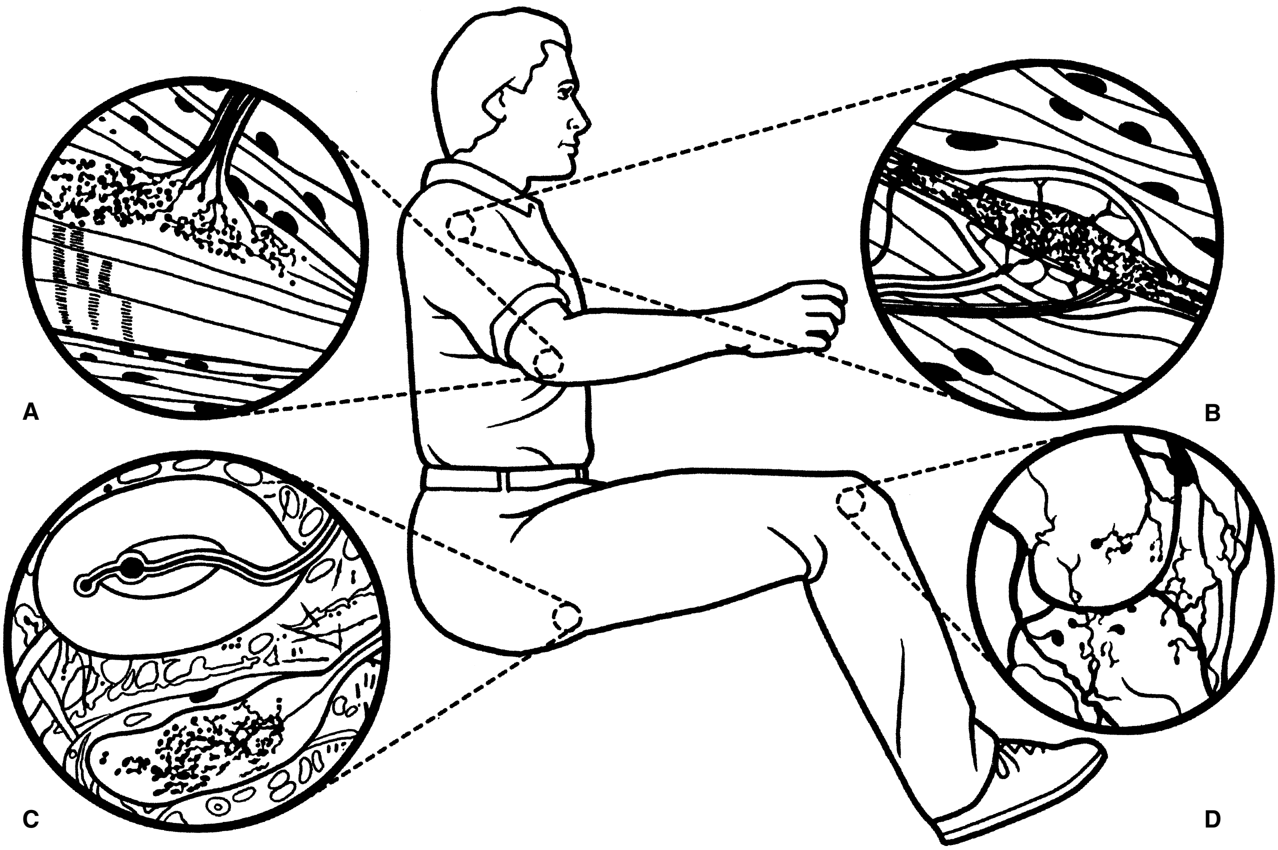


FIGURE 6-13 Some of the nonvestibular proprioceptive and cutaneous exteroceptive receptors subserving spatial orientation. **A:** Muscle spindle, with central afferent (sensory) and more peripheral efferent (fusimotor) innervations. **B:** Golgi tendon organ. **C:** Lamellated, spray-type, and free-nerve-ending joint receptors. **D:** Two of the many types of mechanoreceptors found in the skin: lamellated Pacinian corpuscles and spray-type Ruffini corpuscles.

spinal reflexes operate to stabilize a joint by providing, in response to an increase in length of a muscle and concomitant stimulation of its included spindles, monosynaptic excitation and contraction of the stretched agonist (e.g., extensor) muscle and disynaptic inhibition and relaxation of its antagonist (e.g., flexor) muscle through the action of an inhibitory interneuron. In addition, tension developed on associated tendon organs results in disynaptic inhibition of the agonist muscle, thereby regulating the amount of contraction generated. The myotatic reflex mechanism is the foundation of posture and locomotion. Modification of these and other basic spinal reflexes by organized facilitatory or inhibitory intervention originating at higher neural levels, either through direct action on skeletomotor (α) neurons or through stimulation of fusimotor (primarily γ) neurons to muscle spindles, results in sustained postural equilibrium and other purposive motor behavior. Moreover, some researchers have speculated that when certain types of SD occur during flight this organized modification of spinal reflexes is interrupted as cerebral cortical control of motor activity is replaced by lower brainstem and spinal control. Perhaps the "frozen-on-the-controls" type of disorientation-induced deterioration of flying ability is a reflection of primitive reflexes caused by disorganization of higher neural functions.

Despite the obvious importance of the muscle spindles and tendon organs in the control of motor activity, there is little evidence to indicate that their response to orientational stimuli, such as when one stands vertically in a 1-G environment, results in any corresponding conscious proprioceptive percept. Nevertheless, it is known that the dorsal columns and other ascending spinal tracts carry muscle afferent information to medullary and thalamic relay nuclei and then to the cerebral sensory cortex. Furthermore, extensive projections into the cerebellum, through dorsal and ventral spinocerebellar tracts, ensure that proprioceptive information from the afferent terminations of the muscle spindles and tendon organs is integrated with other orientational information and is relayed to the vestibular nuclei, cerebral cortex, and elsewhere as needed.

Joint Sensation

In contrast to the stimulation with the so-called muscle and tendon senses discussed earlier, it has been well established that sensory information from the joints does reach consciousness. In fact, the threshold for perception of joint motion and position can be quite low: as low as 0.5 degree for the knee joint when moved at a rate greater than 1.0 degree/s. The receptors in the joints are of three types as shown in Figure 6-13C: (a) lamellated or encapsulated Pacinian corpuscle-like end organs, (b) spray-type structures, known as *Ruffini-like endings* when found in joint capsules and *Golgi tendon organs* when found in ligaments, and (c) free nerve endings. The Pacinian corpuscle-like terminals are rapidly adapting and are sensitive to quick movement of the joint, whereas both of the spray-type endings are slowly adapting and serve to signal slow joint movement and joint position. There is evidence that polysynaptic spinal reflexes can be elicited by stimulation of joint receptors, but their nature and extent are not well understood. Proprioceptive information from the joint receptors projects through the dorsal funiculi eventually to the cerebral sensory cortex and through the spinocerebellar tracts to the anterior lobe of the cerebellum.

One must not infer from this discussion that only muscles, tendons, and joints have proprioceptive sensory receptors. Both lamellated and spray-type receptors, as well as free nerve endings, are found in fascia, aponeuroses, and other connective tissues of the musculoskeletal system, and they presumably provide proprioceptive information to the central nervous system.

Cutaneous Exteroceptors

The exteroceptors of the skin include mechanoreceptors, which respond to touch and pressure; thermoreceptors, which respond to heat and cold; and nociceptors, which respond to noxious mechanical and/or thermal events and give rise to sensations of pain. Of the cutaneous exteroceptors, only the mechanoreceptors contribute significantly to orientation.

A variety of receptors are involved in cutaneous mechanoreception: spray-type Ruffini corpuscles, lamellated Pacinian and Meissner corpuscles, branched and straight lanceolate terminals, Merkel Cells, and free nerve endings (Figure 6-13D). The response patterns of mechanoreceptors are also numerous: 11 different types of responses, varying from high-frequency transient detection through several modes of velocity detection to more or less static displacement detection, have been recognized. Pacinian corpuscles and certain receptors associated with hair follicles are very rapidly adapting and have the highest mechanical frequency responses responding to sinusoidal skin displacements in the range of 50 to 400 Hz. Therefore, they are well suited to monitor vibration and transient touch stimuli. Ruffini corpuscles are slowly adapting and, therefore, respond primarily to sustained touch and pressure stimuli. Merkel cells appear to have a moderately slowly adapting response making them suitable for monitoring static skin displacement and velocity. Meissner corpuscles seem to primarily detect velocity of skin deformation. Other receptors provide various types of responses to complete the spectrum of mechanical stimuli that can be sensed through the skin. The mechanical threshold for the touch receptors is quite low at less than 0.03 dyne/cm^2 on the thumb. In comparison, the labyrinthine receptors subserving audition are 100 times lower at 1-dB sound pressure level representing 0.0002 dyne/cm^2.

Afferent information from the described mechanoreceptors is conveyed to the cerebral cortex mainly by way of the dorsal funiculi and medullary relay nuclei into the medial lemnisci and thalamocortical projections. The dorsal spinocerebellar tract and other tracts to the cerebellum provide the pathways by which cutaneous exteroceptive information reaches the cerebellum and is integrated with proprioceptive information from muscles, tendon, joints, and vestibular end organs. Tactile information using proprioceptive prostheses have been tested to improve system awareness and spatial orientation (19). Conversely, some modern "glass cockpit" aircraft have models with non–moving control sticks, which effectively remove tactile information, making the pilot rely solely on visual information. These newer designs integrate simulated force on controls, a feature first used on the F-16 in the 1970s (20).

Auditory Orientation

On the surface of the Earth, the ability to determine the location of a sound source can play a role in spatial orientation as evidenced by the fact that a revolving sound source can create a sense of self-rotation, and elicit reflex compensatory and anticompensatory eye movements called *audiokinetic nystagmus*. Differential filtering of incident sound energy by the ears, head, and shoulders at different relative locations of the sound source provides the ability to discriminate sound location. Part of this discrimination process involves analysis of interaural differences in arrival time of congruent sounds; but direction-dependent changes in spectral characteristics of incident sound energies allow the listener to localize sounds in elevation, azimuth, and to some extent range, even when the interaural arrival times are not different.

In aircraft, binaural sound localization has been of little use in spatial orientation because of high ambient noise levels and the absence of audible external sound sources. Pilots do extract some orientational information, however, from the auditory cues provided by the rush of air past the airframe. Sound frequencies and intensities characteristic of various airspeeds and angles of attack are recognized by the experienced pilot who uses them in conjunction with other orientation information to create a percept of velocity and pitch attitude of the aircraft, particularly with sailplanes. However, as aircraft have become more capable and pilots have become more insulated from such acoustic stimuli, the importance of auditory orientation cues in flying has diminished. Experimentally, a multiple speaker system in a simulator in a global array has been demonstrated to provide orientation information (21).

SPATIAL DISORIENTATION

"The evolution of humans saw us develop over millions of years as an aquatic, terrestrial, and even arboreal creature, but never an aerial one. During this development, humans were subjected to many different varieties of transient motions, but not to relatively sustained linear and angular accelerations commonly experienced in aviation. As a result, humans acquired sensory systems well suited to maneuvering under our own power on the surface of the Earth but poorly suited for flying. Even birds, whose primary mode of locomotion is flying, are unable to maintain spatial orientation and safe flight when deprived of vision by fog or clouds. Only bats seem to have developed the ability to fly without vision by replacing vision with auditory echolocation. Considering our phylogenetic heritage, it should come as no surprise that our sudden entry into the aerial environment resulted in a mismatch between the orientational demands of the new environment and our innate ability to orient. The manifestation of this mismatch is SD (22)."

Illusions in Flight

An illusion is a false percept. An orientational illusion is a false percept of one's position or motion, either linear or angular relative to the plane of the Earth's surface. A great number of orientational illusions occur during flight: some named, others unnamed; some understood, others not understood. Those that are sufficiently impressive to cause pilots to report them, whether because of their responsibility or because of their emotional impact, have been described in the aeromedical literature and will be discussed here. In flight, illusions are categorized into those resulting primarily from visual misperceptions and those involving primarily vestibular errors.

Visual Illusions

We shall organize the in-flight visual illusions according to the primary, the focal mode being visual processing or ambient mode. Although this categorization is somewhat arbitrary and may seem too coarse in some cases, it serves to emphasize the dichotomous nature of visual orientation information processing. We shall begin with illusions involving primarily focal vision.

Shape Constancy

To appreciate how false shape constancy cueing can create orientational illusions in-flight, consider the example provided by a runway that is constructed on other than level terrain. Figure 6-14A shows the pilot's view of the runway during an approach to landing and demonstrates the linear perspective and foreshortening of the runway that the pilot associates with a 3-degree approach slope. If the runway slopes upward 1 degrees (a rise of only 35 m for a 2-km runway), the foreshortening of the runway for a pilot on a 3-degree approach slope is substantially less (i.e., the

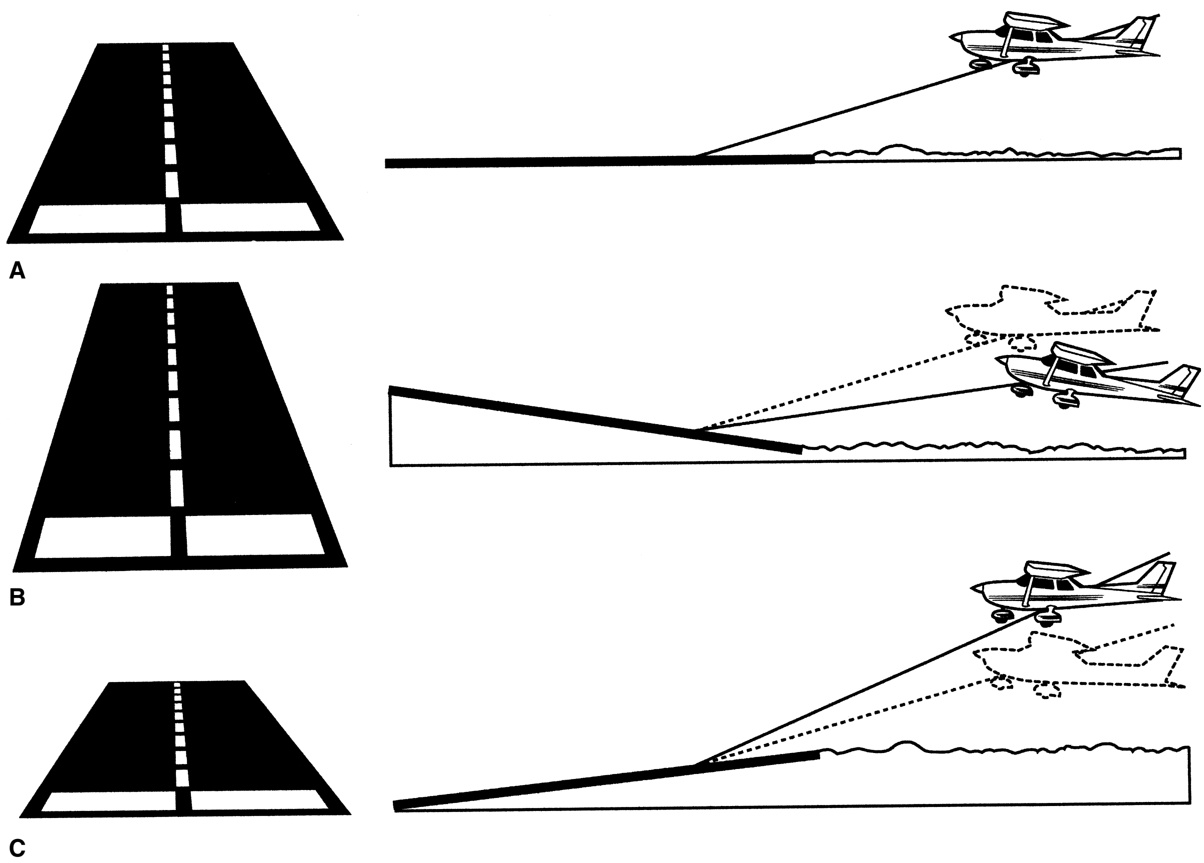


FIGURE 6-14 Effect of runway slope on the pilot's image of runway during final approach (*left*) and the potential effect on the approach slope angle flown (*right*). **A:** Flat runway-normal approach. **B:** An upsloping runway creates the illusion of being high on approach—pilot flies the approach too low. **C:** A downsloping runway has the opposite effect.

height of the retinal image of the runway is greater) than it would be if the runway were level. This can give the pilot the illusion of being too high on the approach. The pilot's natural response to such an illusion is to reshape the image of the runway by seeking a shallower approach slope (Figure 6-14B). This response, of course, could be hazardous. The opposite situation results when the runway slopes downward. To perceive the accustomed runway shape under this condition, the pilot must fly a steeper approach slope than usual (Figure 6-14C).

Size Constancy

Size constancy is very important in judging distance, and false cues are frequently responsible for aircraft mishaps due to illusions of focal visual origin. Runway width illusions are particularly instructive in this context. A runway that is narrower than a pilot is accustomed can create a hazardous illusion on approach to landing. Size constancy causes the pilot to perceive the narrow runway to be farther away (i.e., that they are higher) than it actually is and the pilot may flare too late touching down sooner than expected (Figure 6-15B). In contrast, a runway that is wider than a pilot is accustomed to can lead to the illusion of being closer to the runway (i.e., lower) than reality, and the pilot may flare too soon and drop in from too high above the runway (Figure 6-15C). Both of these runway-width illusions are especially troublesome at night when peripheral visual orientation cues are largely absent. The common tendency for pilots to flare too high at night results partly from the fact that runway lights, being displaced laterally from the actual edge of the runway, make the runway seem wider and, therefore, closer than it actually is. However, a much more serious problem at night is the tendency for pilots to land short of the runway when arriving at an unfamiliar airport having a runway that is narrower than one they are accustomed to.

The slope and composition of the terrain under the approach path can also influence the pilot's judgment of height above the touchdown point. If the terrain descends to the approach end of the runway, the pilot tends to fly a steeper approach than if the approach terrain were level (Figure 6-16A). If the approach terrain slopes up to the runway, on the other hand, the pilot tends to fly a less steep approach (Figure 6-16B). Although the estimation of height above the approach terrain depends on both focal and ambient vision, the contribution of focal vision is particularly clear. Consider the pilot who looks at a building below the aircraft and perceiving it to be closer than it is, seeks a higher approach slope.

Focal vision and size constancy are also responsible for the poor height and distance judgments pilots sometimes make when flying over terrain having an unfamiliar composition (Figure 6-17). An example of this is the reported tendency

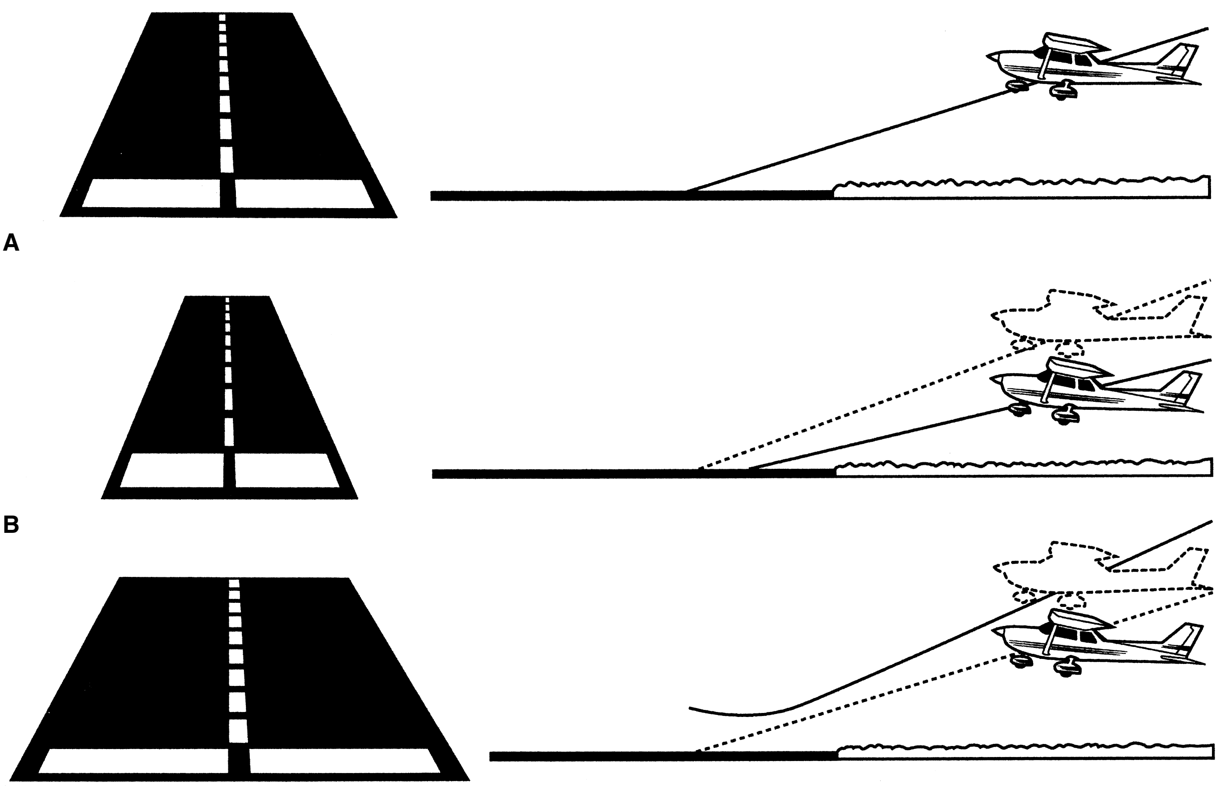


FIGURE 6-15 Effect of runway width on the pilot's image of runway (*left*) and the potential effect on approach flown (*right*). **A:** Accustomed width—normal approach. **B:** A narrow runway makes the pilot feel higher than actually, the approach is too low and flares too late. **C:** A wide runway gives the illusion of being closer than it actually is—the pilot tends to approach too high and flares too soon.

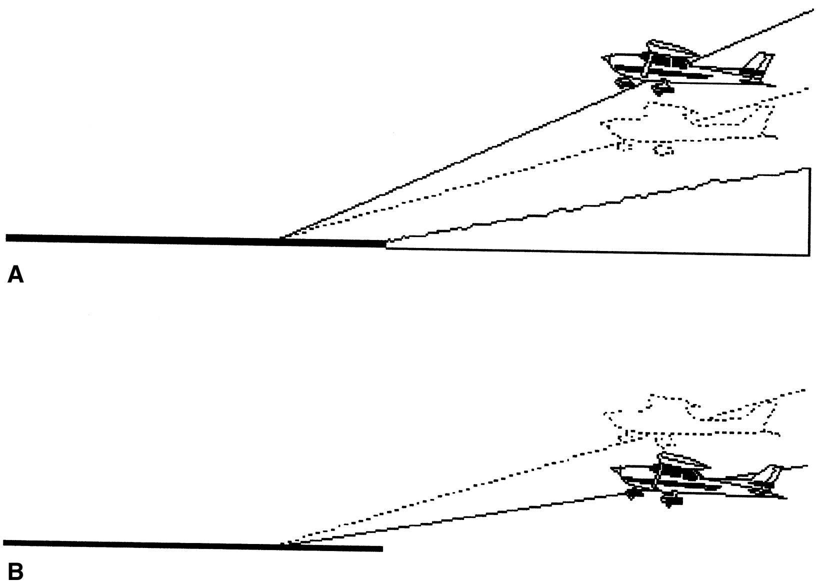


FIGURE 6-16 Potential effect of the slope of the terrain under the approach on the approach slope flown. **A:** The terrain slopes down to the runway; the pilot thinks approach is too shallow and steepens it. **B:** Upsloping terrain makes the pilot think approach is too high, and corrects by making the approach too shallow.

to misjudge height when landing in the Aleutians, where the evergreen trees are much smaller than those to which most pilots are accustomed. Such height estimation difficulties are by no means restricted to the approach and landing phases of flight. One fatal mishap occurred during air combat training over the Southwest desert when the pilot of a high-performance fighter presumably misjudged his height over the desert floor because of the small, sparse vegetation and was unable to arrest his deliberate descent to a ground-hugging altitude (23). In-flight illusions can also occur by mistaking one aircraft for another during overtake, such as confusing the smaller United States Air Force (USAF)/Lockheed C-141 and C-5 or the Boeing 737 with the much larger Airbus.

Aerial Perspective

Aerial perspective may also play a role in deceiving the pilot, and the approach-to-landing scenario again provides examples. In daytime, fog or haze can make a runway appear farther away as a result of the loss of visual discrimination. At night, runway and approach lights in fog or rain appear less bright than they do in clear weather and can create the illusion that they are farther away. It has even been reported that a pilot can have an illusion of banking to the right, for example, if the runway lights are brighter on the right side of the runway than they are on the left. Another hazardous illusion of this type can occur during approach to landing in a shallow fog or haze, especially during a night approach. The vertical visibility under such conditions is much better than the horizontal visibility, so descent into the fog causes the more distant approach or runway lights to diminish in intensity at the same time that the peripheral visual cues are suddenly occluded by the fog. Haziness implies increased distance and the result is an illusion that the aircraft has pitched up, with the concomitant danger of a nose-down corrective action by the pilot.

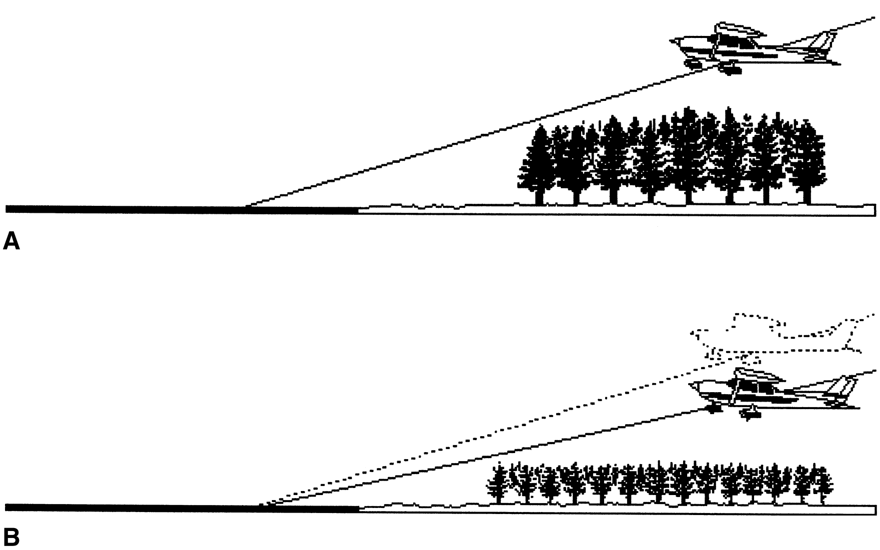


FIGURE 6-17 Potential effect of unfamiliar composition of approach terrain on the approach slope flown. **A:** Normal approach over trees of familiar size. **B:** Unusually small trees under the approach path make the pilot think approach is too high, so the approach is made lower than usual.

Absent Focal Cues

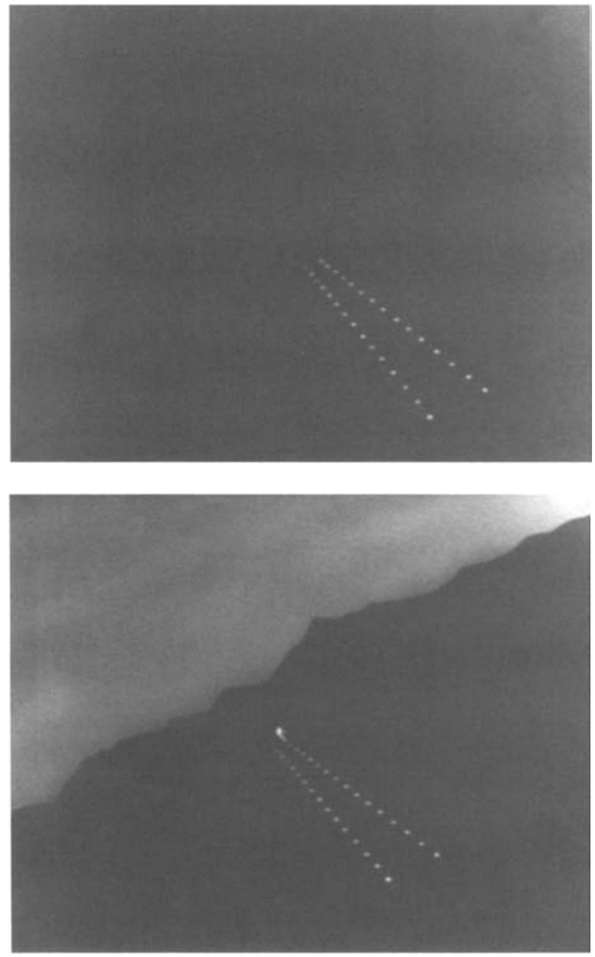
A well-known pair of approach-to-landing situations that create illusions because of the absence of adequate focal visual orientation cues are the smooth-water (glassy-water) and snow-covered approaches. A seaplane pilot's perception of height is degraded substantially when the water below is still; for that reason, a pilot routinely sets up a safe descent rate and waits for the seaplane to touch down, rather than attempting to flare to a landing when the water is smooth. A blanket of fresh snow on the ground and runway also deprives the pilot of visual cues to estimate height, thereby making the approach extremely difficult. Again, approaches are not the only scenarios in which smooth water and fresh snow cause problems. A number of aircraft have crashed as a result of pilots maneuvering over smooth water or snow-covered ground and misjudging their height above the surface.

Absent Ambient Cues

Two conditions that create considerable difficulty for the pilot during runway approach are the black-hole and whiteout approaches. Normal runway approaches require the use of focal and ambient vision but these two types of approaches force the pilot to only use focal vision to execute the landing. A black-hole approach is one that is made on a dark night over water or unlighted terrain to a runway beyond which the horizon is indiscernible, the worst case being when only the runway lights are visible (Figure 6-18). Without peripheral visual cues to help provide orientation relative to the Earth, the pilot tends to feel that the aircraft is stable and situated appropriately but that the runway itself moves about or remains malpositioned (is downsloping, for example). Such illusions make the black-hole approach difficult and dangerous and often result in a landing far short of the runway. A particularly hazardous type of black-hole approach is one made under conditions of total darkness except for the runway and the lights of a city on rising terrain beyond the runway. Under these conditions, the pilot may try to maintain a constant vertical visual angle for the distant city lights causing the aircraft to arc far below the intended approach as it gets closer to the runway (Figure 6-19). An alternative explanation is that the pilot falsely perceives through ambient vision that the rising terrain is flat and as a result lowers the approach slope accordingly.

An approach made under whiteout conditions can be as difficult as a black-hole approach for essentially the same reason, lack of sufficient ambient visual orientation cues. There are actually two types of whiteout, the atmospheric whiteout and the blowing-snow whiteout. In the atmospheric whiteout, a snow-covered ground merges with an overcast sky creating a condition in which ground textural cues are absent and the horizon is indistinguishable. Although visibility may be unrestricted in the atmospheric whiteout, there is essentially nothing to see except the runway markers; therefore, an approach made in this condition must be accomplished with a close eye on the altitude and attitude instruments to prevent SD and inadvertent ground contact. In the blowing-snow whiteout, visibility is restricted drastically by snowflakes, and often those snowflakes have been driven into the air by the propeller or rotor wash of the affected aircraft. Helicopter landings on snow-covered ground are particularly likely to create blowing-snow whiteouts, although similar conditions exist for helicopters in dusty and sandy environments. Typically, a helicopter pilot trying to maintain visual contact with the ground during a rotor-induced whiteout will get into an unrecognized drift to one side contact the ground with sufficient lateral motion to cause the craft to roll until a rotor strikes the ground. This situation creates a condition known as *dynamic rollover*. Pilots flying in environments where whiteouts may occur must be made aware of the hazards of whiteout approaches, because disorientation usually occurs unexpectedly under visual rather than instrument meteorologic conditions.

Another condition in which a pilot is apt to make a serious misjudgment is while closing on another aircraft at



A

B

FIGURE 6-18 Effect of loss of ambient visual orientation cues on the perception of runway orientation during a black-hole approach. **A:** When ambient visual orientation cues are absent, the pilot feels horizontal and (in this example) perceives the runway to be tilted left and upsloping. **B:** With the horizon visible, the pilot orients self correctly with peripheral vision and the runway appears horizontal in central vision.

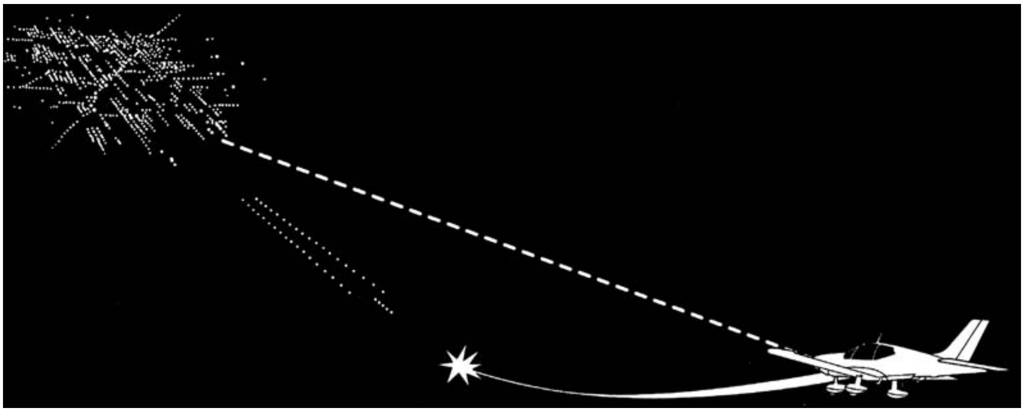


FIGURE 6-19 A common and particularly dangerous type of black-hole approach, in which the pilot perceives the distant city to be flat and arcs below the desired approach slope.

high speed. When a pilot has numerous peripheral visual cues to establish the position and velocity relative to the Earth of himself or herself and the target, the pilot's tracking and closing problem is not much different from what it would be on the ground if he or she were giving chase to a moving target. When relative position and closure rate cues must come from only foveal vision, at night or under other conditions of reduced visibility, the tracking and closing problem is much more difficult. An overshoot, or worse a midair collision, can easily result from the perceptual difficulties inherent in such circumstances, especially when the pilot lacks experience in an environment devoid of peripheral visual cues.

A related phenomenon that pilots need to be aware of is the dip illusion. It occurs during formation flying at night, when one aircraft is in trail behind another. To avoid wake turbulence and maintain sight of the lead aircraft, the pilot in trail needs to keep the aircraft at a small but constant angle below the lead aircraft. This is done by placing the image of the lead aircraft in a particular position on the windscreen and keeping it there. If the pilot is told to "take spacing" (separate) to 10 km (5 nautical miles), for every 1 degree below the lead, the pilot is lower by 1.7% (sin 1 degree) of the distance behind the lead. Therefore, if the pilot is 2 degrees below lead and keeps the image of the lead aircraft at the same spot on the windscreen all the way back to 10 km, the trailing aircraft will descend to 350 m (1,100 ft) below the lead aircraft. To make matters worse, when the aircraft in trail slows down to establish separation its pitch attitude (angle of attack) increases by several degrees; if the pilot does not compensate for this additional angle and tries to maintain the lead aircraft image in the same relative position, he or she can double or even triple the altitude difference between the two aircraft. In the absence of ambient visual orientation cues, the pilot cannot detect the large loss of altitude unless he or she monitors the flight instruments and may inadvertently "dip" far below the intended flight path. Clearly this situation would be extremely hazardous if it were to occur at low altitude or during maneuvers in which altitude separation from other aircraft is critical.

Autokinesis

One puzzling illusion that occurs when ambient visual orientation cues are minimal is visual autokinesis (Figure 6-20). A small, dim light seen against a dark background is an ideal stimulus for producing autokinesis. After 6 to 12 seconds of visually fixating on the light, one can observe it move at 20 degrees/s or less in a particular direction or in several directions in succession, but there is little apparent displacement of the object fixated. In general, the larger and brighter the object the less the autokinetic effect. The physiologic mechanism of visual autokinesis is not understood. One suggested explanation for the autokinesis phenomenon is that the eyes

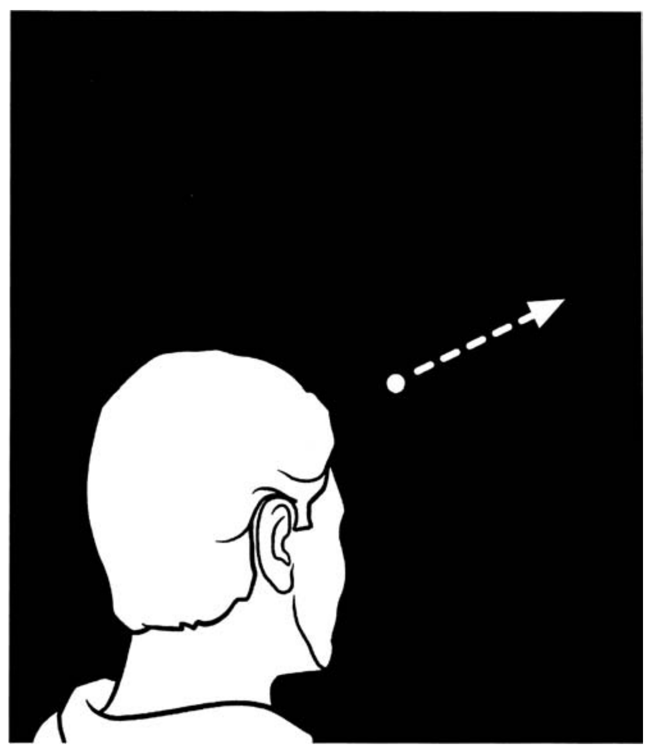


FIGURE 6-20 Visual autokinesis. A small, solitary light or small group of lights seen in the dark can appear to move, when in fact they are stationary.

tend to drift involuntarily, perhaps because of inadequate or inappropriate vestibular stabilization, and that checking the drift requires unrecognized oculomotor efferent activity having sensory correlates that create the illusion.

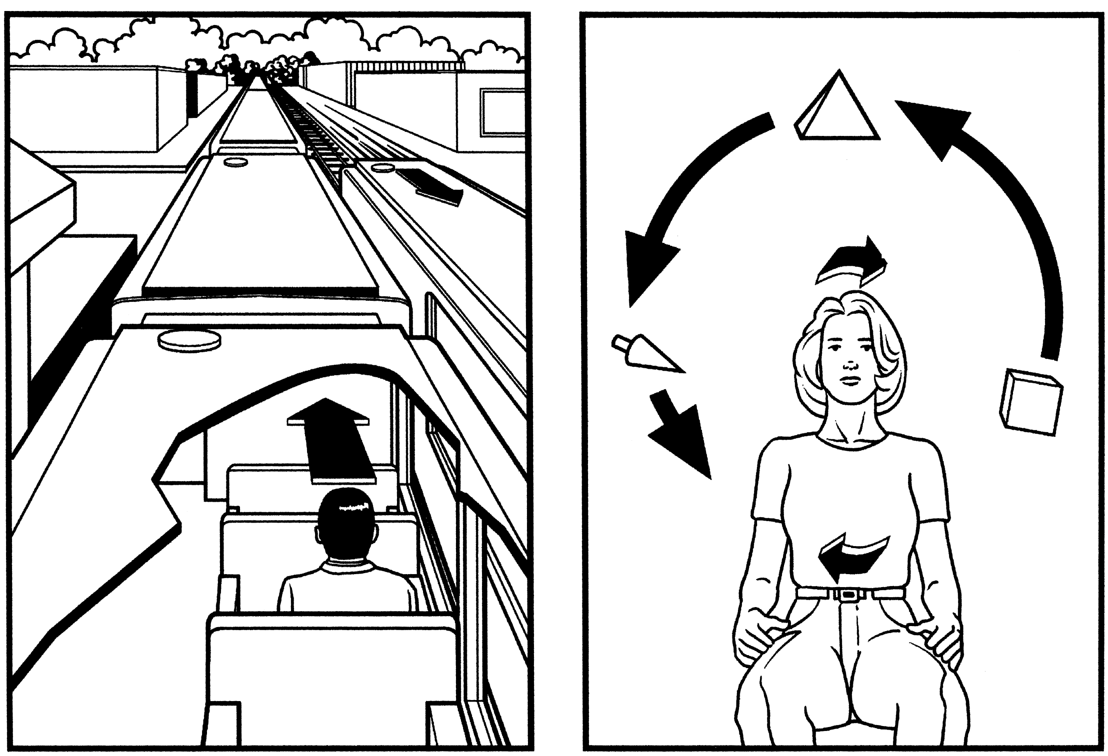
Whatever the mechanism, the effect of visual autokinesis on pilots is of some importance. Anecdotes abound of pilots who fixate on a star or a stationary ground light at night and, after perceiving it in motion because of autokinesis, mistake it for another aircraft and try to intercept or join up with it. Another untoward effect of the illusion occurs when a pilot flying at night, following or intercepting another aircraft, perceives another aircraft to be moving erratically when in fact it is not; the unnecessary and undesirable control inputs that the pilot makes to compensate for the illusory movement of the target represent increased work and wasted motion at best and an operational hazard at worst.

To help avoid or reduce the autokinetic illusion, the pilot should try to maintain a well-structured visual environment in which spatial orientation is unambiguous. Because this is rarely possible in night flying, it has been suggested that (a) the pilot's gaze should be shifted frequently to avoid prolonged fixation on a target light, (b) the target should be viewed beside or through and in reference to a relatively stationary structure such as a canopy bow, (c) the pilot should make eye, head, and body movements to try to destroy the illusion, and (d) as always, the pilot should monitor the flight instruments to help prevent or resolve any perceptual conflict. Equipping aircraft with more than one light or with luminescent strips to enhance recognition at night probably has helped reduce problems with autokinesis.

Vection Illusions

So far, this chapter has dealt with visual illusions created by excessive orientation processing demands being placed on focal vision when adequate orientation cues are not available through ambient vision or when strong but false orientation cues are received through focal vision. Ambient vision can itself be responsible for creating orientational illusions, however, when orientation cues received in the visual periphery are misleading or misinterpreted. Probably the most compelling of such illusions are the vection illusions. Vection is the visually induced perception of self-motion in the spatial environment and can be a sensation of linear motion (linear vection) or angular motion (angular vection).

Nearly everyone who drives an automobile has experienced one very common linear vection illusion; a driver waiting in his or her car at a stoplight and a presumably stationary vehicle in the adjacent lane creeps forward compelling an illusion that one's own car is rolling backward, prompting a swift but surprisingly ineffectual stomp on the brakes. Similarly, if a passenger is sitting in a stationary train and the train on the adjacent track begins to move, the strong sensation of self-motion in the opposite direction can be experienced (Figure 6-21A). Linear vection is one of the factors that makes close formation flying so difficult because the pilot can never



A B

FIGURE 6-21 Vection illusions. **A:** Linear vection. In this example, the adjacent vehicle seen moving aft in his peripheral vision causes the subject to feel as though moving forward. **B:** Angular vection. Objects seen revolving around the subject in the flight simulator leads to a sense of self-rotation in the opposite direction—in this case, a rolling motion to the right.

be sure whether his or her aircraft or that of the pilot's lead or wingman is responsible for the perceived relative motion.

Angular vection occurs when peripheral visual cues convey information that one is rotating; the perceived rotation can be in pitch, roll, yaw, or any other plane of movement. Although angular vection illusions are not common in everyday life, they can be generated readily in a laboratory by enclosing a stationary subject in a rotating striped drum. Usually in the 10 seconds after the visual motion begins, the subject perceives that he or she rather than the striped drum is rotating. A pilot can experience angular vection if the rotating anticollision light on the aircraft is left on during flight through clouds or fog. The revolving reflection provides a strong ambient visual stimulus signaling rotation in the yaw plane.

Another example of vection illusions is the so-called Star Wars effect, named after the popular motion picture because of its vection-inducing visual effects. This phenomenon involves linearly and angularly moving reflections of ground lights off the curved interior surface of an aircraft canopy, which create disconcerting sensations of motion that conflict with the actual motion of the aircraft.

Fortunately, vection illusions are not all bad. The most advanced flight simulators depend on linear and angular vection to create the illusion of flight (Figure 6-21B). When the visual flight environment is dynamically portrayed in wide-field-of-view, infinity-optics flight simulators, the illusion of actual flight is so compelling that additional mechanical motion is not needed, although, mechanically generated motion-onset cues do seem to improve the fidelity of the simulation. Movie theatre and virtual reality rides exploit this phenomena to great advantage. Examples of using vection to produce the sensation of motion can be best demonstrated by observing the more popular rides at Disney World. As mentioned earlier, one of the most popular rides at Epcot is Soarin, which is a mix of vection with subtle and synchronized motion cues. The same can be said about some of the new rides in Las Vegas, such as Journey to Atlantis.

False Horizons and Surface Planes

Often the horizon perceived through ambient vision is not really horizontal. Quite naturally, this misperception of the horizontal creates hazards in flight. A sloping cloud deck, for example, will be perceived as horizontal if it extends for any great distance into the pilot's peripheral vision (Figure 6-22). Uniformly sloping terrain, particularly upsloping terrain, can create an illusion of being horizontal with disastrous consequences for the deceived pilot. Many aircraft have crashed as a result of the pilot's misperception of a canyon with an apparently level floor, only to find that the floor actually rose faster than the airplane could climb. At night, the lights of a city built on sloping terrain can create the false impression that the extended plane of the city lights is the horizontal plane of the Earth's surface, as already noted (Figure 6-19). A distant rain shower can obscure the real horizon and create the impression of a horizon at the proximal edge (base) of the rainfall. If the shower is seen just beyond the runway during an approach to landing, the pilot may misjudge the pitch attitude of his or her aircraft and make inappropriate pitch corrections on the approach.

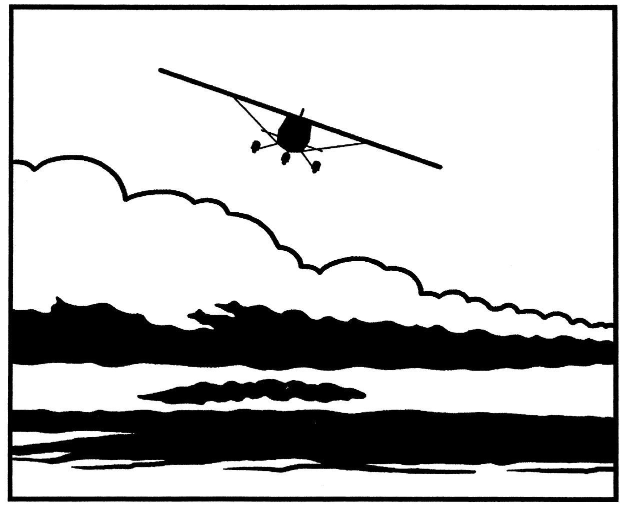


FIGURE 6-22 A sloping cloud deck, which the pilot misperceives as a horizontal surface.

A unique, false horizon phenomena can occur at very high latitudes. During the long hours of darkness, the aurora may appear and comprise the only source of illumination. The shimmering curtains plus ground reflection may form a sky/surface horizon or when viewed peripherally provide a vection illusion. If the constantly shifting curtain of the aurora rotates, a 90-degree rotation is not unusual; the pilot may be tempted to roll with the horizon illusion (Figure 6-23).

FIGURE 6-23 Aurora Borealis appears as a false horizon. As aurora curtain shifts, pilot attempts to follow the false horizon.

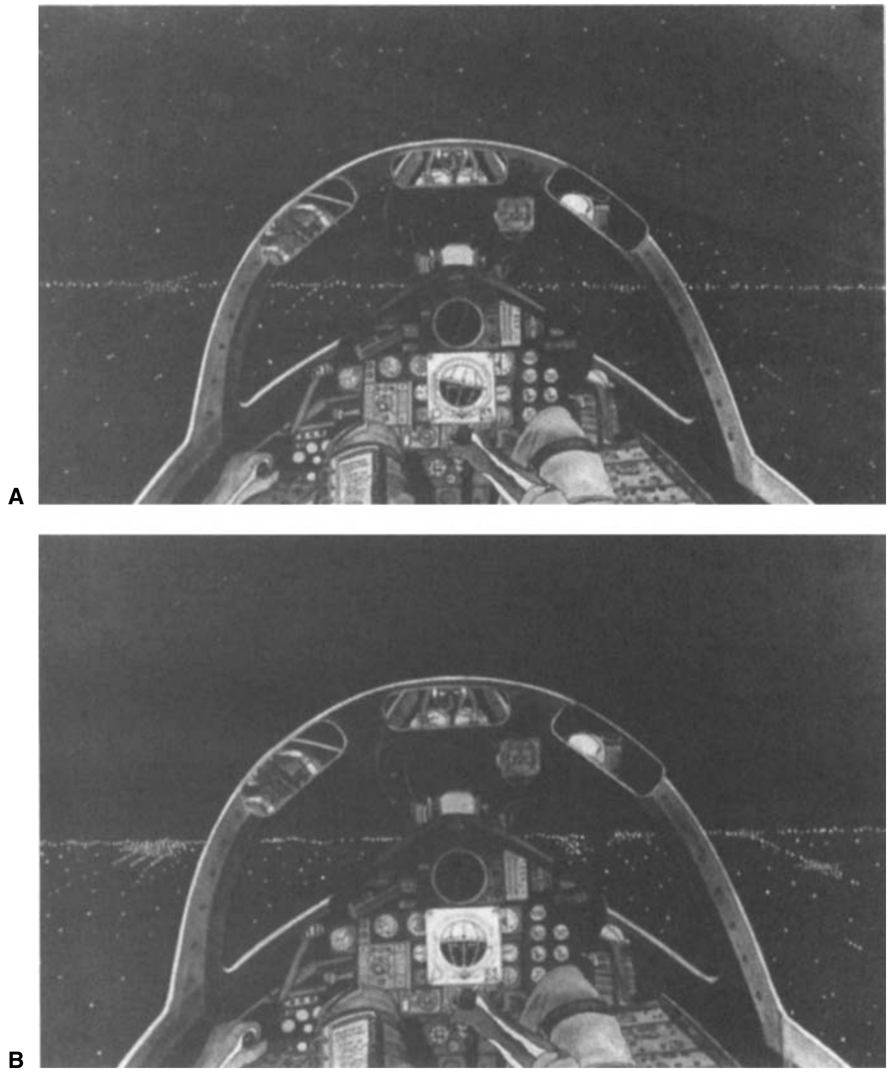


FIGURE 6-24 Misperception of the horizontal at night. **A:** Ground lights appearing to be stars cause the Earth and sky to blend and a false horizon to be perceived. **B:** Blending of overcast sky with unlighted terrain or water causes the horizon to appear lower than is actually the case.

Pilots are especially susceptible to misperception of the horizontal while flying at night (Figures 6-24A and B). Isolated ground lights may appear to a pilot as stars leading to the illusion of being in a nose-high or one-wing-low attitude. Flying under such a false impression can, of course, be fatal. Frequently, no stars are visible because of overcast conditions and unlighted areas of terrain blend with the dark overcast to create the illusion that the unlighted terrain is part of the sky. One extremely hazardous situation is when a takeoff is made over an ocean or other large body of water that cannot be distinguished visually from the night sky. Many pilots in this situation have perceived the shoreline receding beneath them to be the horizon, and some have responded to this false ‘‘pitch-up’’ percept with disastrous consequences.

Pilots flying at high altitudes can sometimes experience difficulties with control of aircraft attitude, because at high altitudes the horizon is lower with respect to the plane at level flight than it is at lower altitudes, where most pilots are accustomed to flying. As a reasonable approximation, the angle of depression of the horizon in degrees equals the square root of the altitude in kilometers. A pilot flying at an altitude of 15 km (49,000 ft) sees the horizon almost 4 degrees below the extension of the horizontal plane. If a pilot visually orients to the view from the left cockpit window, she/he may be inclined to fly with the left wing 4 degrees down to level it with the horizon. If this is done and the pilot then looks out through the right window, the right wing would be seen 8 degrees above the horizon, with half of that elevation due to his/her own erroneous control input. The pilot may also experience problems with pitch control, because the depressed horizon could cause him/her to perceive a false 4-degree nose-high pitch attitude.

Another result of false ambient visual orientational cueing is the lean-on-the-sun illusion. On the ground, we are accustomed to seeing the brighter visual surround above and the darker one below, regardless of the position of the sun. The direction of this gradient in light intensity helps us orient with respect to the surface of the Earth. However, in clouds such a gradient usually does not exist, and when it does, due to sunlight being able to penetrate the moisture, a perceived verticality is often experienced that will cause the pilot to orient the aircraft's bank with respect to the light and not the gravitational vertical. The lean-on-the-sun illusion stems from the sun not being directly overhead and as a consequence a pilot flying in a thin cloud layer tends to falsely perceive the direction of the sun as directly overhead. This misperception causes the pilot to bank in the direction of the sun, hence the name of the illusion. Extreme episodes have occurred after acrobatic or air combat maneuvering in near atmospheric whiteout conditions that often exist over water, when a recovering pilot will orient himself or herself with the sun overhead, even if this results in a bank angle of more than 90 degrees.

Other False Ambient Cues

One very important aspect of in-flight ambient visual orientational cueing is the stabilizing effect of the surrounding instrument panel, glare shield, and canopy bow or windshield frame, especially the reflection of panel lights and other cockpit structures off the windshield or canopy at night. When the aircraft rolls or pitches while the pilot is inattentive, the stable visual surround provided by these objects tends to cause the motion not to be perceived, although it may be at a rate well above the usual threshold for vestibular motion perception. While flying at night or in instrument weather, a pilot may have a false sense of security because of the lack of perceived motion as his or her dominant orientational sense locks onto an apparently stable ambient visual environment. Of course, this falsely stabilizing effect does not occur when the visual environment contains valid, spatially orienting ambient visual references (natural horizon, Earth's surface, etc.).

Finally, the disorienting effects of aerial flares should be mentioned. When aerial flares are dropped, they descend and drift with the wind, creating false cues of vertical. Their motion may also create vection illusions. Another phenomenon associated with use of aerial flares at night is the "moth" effect; the size of the ground area illuminated by a dropped flare slowly decreases as the flare descends. Because of the size constancy mechanism of visual orientation discussed earlier, a pilot circling the illuminated area may tend to fly in a descending spiral with gradually decreasing radius. Another important factor is that the aerial flares can be bright enough to reduce the apparent intensity of the aircraft instrument displays and thereby minimize their orientational cueing strength. Laser light shows have been reported to have similar effects.

Vestibular Illusions

The vestibulocerebellar axis processes orientation information from the vestibular, visual, and other sensory systems. In the absence of adequate ambient visual orientation cues, the inadequacies of the vestibular and other orienting senses can result in orientational illusions. It is convenient and conventional to discuss the vestibular illusions in relation to the two functional components of the labyrinth that generate them, the semicircular ducts and the otolith organs.

Somatogyral Illusion

A somatogyral illusion is a false sensation of rotation, or absence of rotation, which results from misperceiving the magnitude or direction of an actual rotation. In essence, somatogyral illusions result from the inability of the semicircular ducts to accurately register a prolonged rotation, that is, sustained angular velocity. When a person is subjected to an angular acceleration about the yaw axis, for example, the angular motion is at first perceived accurately because the dynamics of the cupula-endolymph system cause it to respond as an integrating angular accelerometer (i.e., as a rotation-rate sensor) at stimulus frequencies in the physiologic range (24) (Figure 6-25). If the acceleration is followed immediately by a deceleration, as usually happens in the terrestrial environment, the total sensation of turning one way and then stopping the turn is quite accurate (Figure 6-26). However, if the angular acceleration is followed by a constant angular velocity, not a deceleration, the sensation of rotation progressively lessens and eventually disappears as the cupula gradually returns to its resting position in the absence of an effective angular acceleratory stimulus (Figure 6-27). If the rotating subject is subsequently exposed to an angular deceleration after a period of prolonged constant angular velocity, say after 10 seconds or so of constant-rate turning, the cupula-endolymph system signals a turn in the direction opposite to that of the prolonged

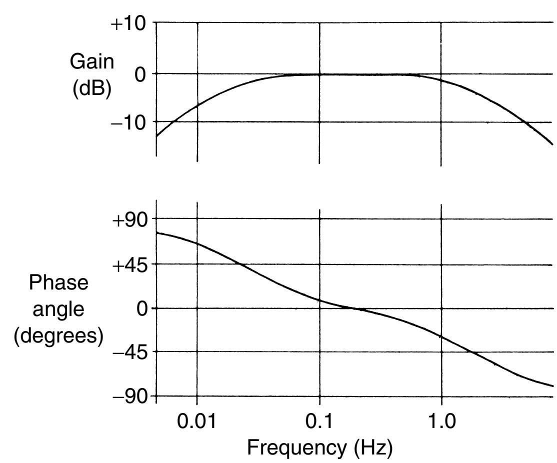


FIGURE 6-25 Transfer characteristics of the semicircular duct system as a function of sinusoidal stimulus frequency. Gain is the ratio of the magnitude of the peak perceived angular velocity to the peak delivered angular velocity; phase angle is a measure of the amount of advance or delay between the peak perceived and peak delivered angular velocities. Note that in the physiologic frequency range (roughly 0.05–1 Hz), perception is accurate; that is, gain is close to unity (0 dB) and phase shift is minimal. At lower stimulus frequencies, however, the gain drops off rapidly and the phase shift approaches 90E, which means that angular velocity becomes difficult to detect and that angular acceleration is perceived as velocity. (Adapted from Peters RA. Dynamics of the vestibular system and their relation to motion perception, spatial disorientation, and illusions. NASA-CR-1309. Washington, DC: National Aeronautics and Space Administration, 1969.)

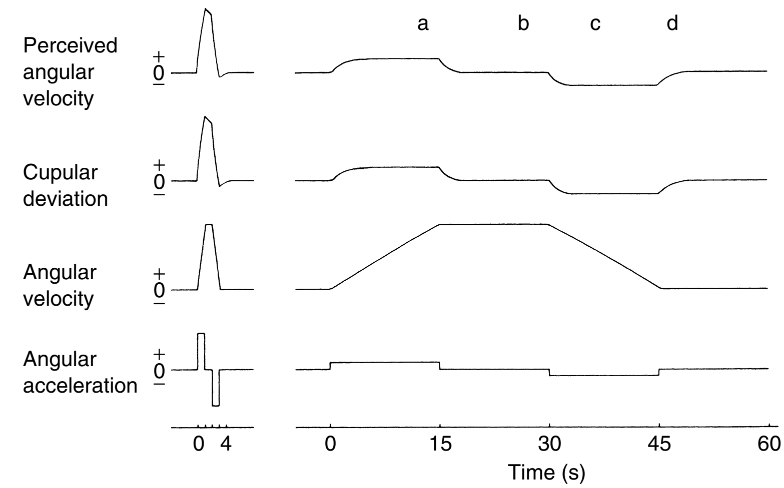


FIGURE 6-26 Effect of the stimulus pattern on the perception of angular velocity. On the left, the high-frequency character of the applied angular acceleration results in a cupular deviation that is nearly proportional to, and perceived angular velocity that is nearly identical to, the angular velocity developed. On the right, the peak angular velocity developed is the same as that on the left, but the low-frequency character of the applied acceleration results in cupular deviation and perceived angular velocity that appear more like the applied acceleration than the resulting velocity. This causes one to perceive: (a) less than the full amount of the angular velocity, (b) absence of rotation while turning persists, (c) a turn in the opposite direction from that of the actual turn, and (d) that turning persists after it has actually stopped. These false percepts are somatogyral illusions.

constant angular velocity, although the person is really only turning less rapidly in the same direction. This occurs because the angular momentum of the rotating endolymph causes it to press against the cupula, forcing the cupula to deviate in the direction of endolymph flow, which is the same direction the cupula would deviate if the subject were to accelerate in the direction opposite to his or her initial acceleration. Even after rotation actually ceases, the sensation of rotation in the direction opposite to that of the sustained angular velocity persists for several seconds to half a minute or longer with a large decelerating rotational impulse. Another more mechanistic definition of somatogyral illusion is any discrepancy between actual and perceived rate of self-rotation that results from an abnormal angular acceleratory stimulus pattern. The term *abnormal* in this case implies the application of low-frequency stimuli outside the useful portion of the transfer characteristics of the semicircular duct system.

During flight under conditions of reduced visibility, somatogyral illusions can be deadly. The graveyard spin is the classic example of how somatogyral illusions can disorient a pilot with fatal results. This situation begins with the pilot intentionally or unintentionally entering a spin (Figure 6-28). At first, the pilot perceives the spin correctly because the angular acceleration associated with entering the spin deviates the cupulae in the appropriate direction to the correct magnitude. However, the longer the spin persists the more the sensation of spinning diminishes, as the cupulae return to their resting positions. If the pilot tries to stop the spin left by applying the opposite rudder, the angular deceleration causes him or her to perceive a spin to the opposite direction, although the real result of the pilot's action is termination of the spin in the original direction. A pilot who is ignorant of the possibility of such an illusion is then likely to make counterproductive rudder inputs to negate the unwanted erroneous sensation of spinning. These control inputs keep the airplane spinning, which gives the pilot the desired sensation of not spinning but does not bring the airplane under control. To extricate one's self from this very hazardous situation, the pilot must read the aircraft flight instruments and apply control inputs to make the instruments give the desired readings. Unfortunately, this may not be easy to do. The angular accelerations created by both the multiple-turn spin and the pilot's spin-recovery

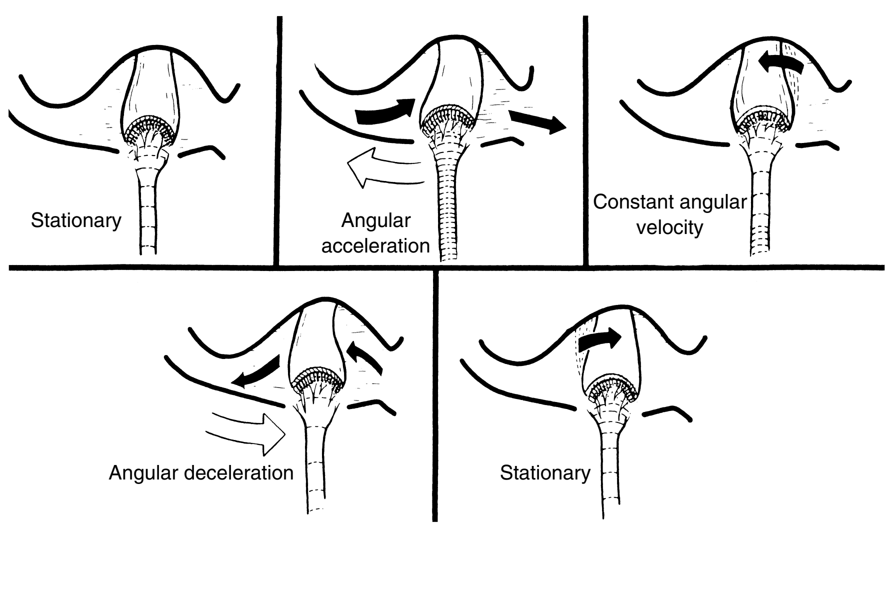


FIGURE 6-27 Representation of the mechanical events occurring in a semicircular duct and the resulting action potentials in the associated ampullary nerve during somatogyral illusions. The angular acceleration pattern applied is that shown in the right side of Figure 6.26.

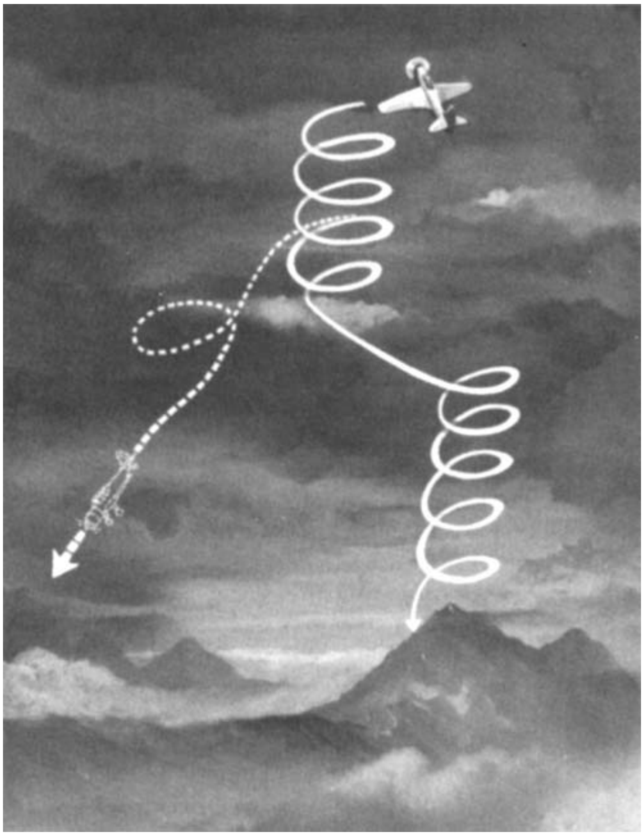


FIGURE 6-28 The graveyard spin. After several turns of a spin, the pilot begins to lose the sensation of spinning. Then, when he or she tries to stop the spin, the resulting somatogyral illusion of spinning in the opposite direction makes the pilot reenter the original spin. (The *solid line* indicates actual motion; the *dotted line* indicates perceived motion.)

attempts can elicit strong but inappropriate vestibulo-ocular reflexes, including nystagmus. In the usual terrestrial environment, these reflexes help stabilize the retinal image of the visual surround; in this situation, however, they only destabilize the retinal image because the visual surround, the cockpit, is already fixed with respect to the pilot. Reading the flight instruments therefore becomes difficult or impossible, and the pilot is left with only the false sensations of rotation to rely on for spatial orientation and aircraft control (25).

Although early aviation provided the graveyard spin as an illusion of the hazardous nature of somatogyral illusions, a much more common example in modern aviation is the graveyard spiral (Figure 6-29). In this situation, the pilot has intentionally or unintentionally got into a prolonged turn with a moderate amount of bank. After a number of seconds in the turn, the pilot loses the sensation of turning because the cupula-endolymph system cannot respond to the constant angular velocity. The percept of being in a bank, as a result of the initial roll into the banked attitude, also decays with time because the net gravitoinertial force vector points toward the floor of the aircraft during coordinated flight (whether the aircraft is in a banked turn or flying straight and level), and the otolith organs and other graviceptors normally signal that down is in the direction of the net sustained gravitoinertial force. As a result, when the pilot tries to stop the turn by rolling back to a wings-level attitude, he or she not only feels a turn in the direction opposite of the original turn but also feels a bank in the direction opposite to the original bank. Unwilling to accept this sensation of making the wrong control input, the hapless pilot rolls back into the original banked turn. Now the pilot's sensation is compatible with the desired mode of flight, but the instruments indicate that the aircraft is losing altitude, because the banked turn is wasting lift, and still turning. So the pilot pulls back on the stick and perhaps adds power to arrest the unwanted descent and regain the lost altitude. This action would be successful if the aircraft were flying wings-level, but with the aircraft in a banked attitude it tightens the turn, serving only to make matters worse. Unless the pilot eventually recognizes the error and rolls out of the unperceived banked turn, he or she will continue to descend in an ever-tightening spiral toward the ground, hence the name graveyard spiral.

Similarly, an illusion exists with roll about the longitudinal axis, the Gillingham illusion. Pilots with restricted visual input trying to recover from excessive roll maneuvers may inadvertently increase roll input while intending to maintain constant bank angle. The pilot will not notice the erroneous control input and in some cases, the aircraft will roll completely inverted (25).

Oculogyral Illusion

An oculogyral illusion is a false perception of motion of an object viewed by a subject. For example, if a vehicle with a subject inside is rotating about a vertical axis at a constant velocity and suddenly stops rotating, the subject experiences not only a somatogyral illusion of rotation in the opposite direction but also an oculogyral illusion of an object in front of him or her moving in the opposite direction. Therefore, a simplified definition of the oculogyral illusion is the visual correlate of the somatogyral illusion; however, its low threshold and lack of total correspondence with presumed cupular deviation suggest a more complex mechanism. The attempt to maintain visual fixation during a vestibulo-ocular reflex elicited by angular acceleration is at least partially responsible for oculogyral illusions. During flight at night or in inclimate weather, an oculogyral illusion generally confirms a somatogyral illusion; the pilot who falsely perceives that he or she is turning in a particular direction also observes the aircraft's instrument panel to be moving in the same direction.

Coriolis Illusion

The vestibular Coriolis effect, also called the *Coriolis cross-coupling effect; vestibular cross-coupling effect*; or simply the *Coriolis illusion*, is another false percept that may result from unusual stimulation of the semicircular duct system. To illustrate this phenomenon, let us consider a subject who has been rotating in the plane of his or her horizontal semicircular ducts (roughly the yaw plane) long enough for the endolymph in those ducts to attain the same angular

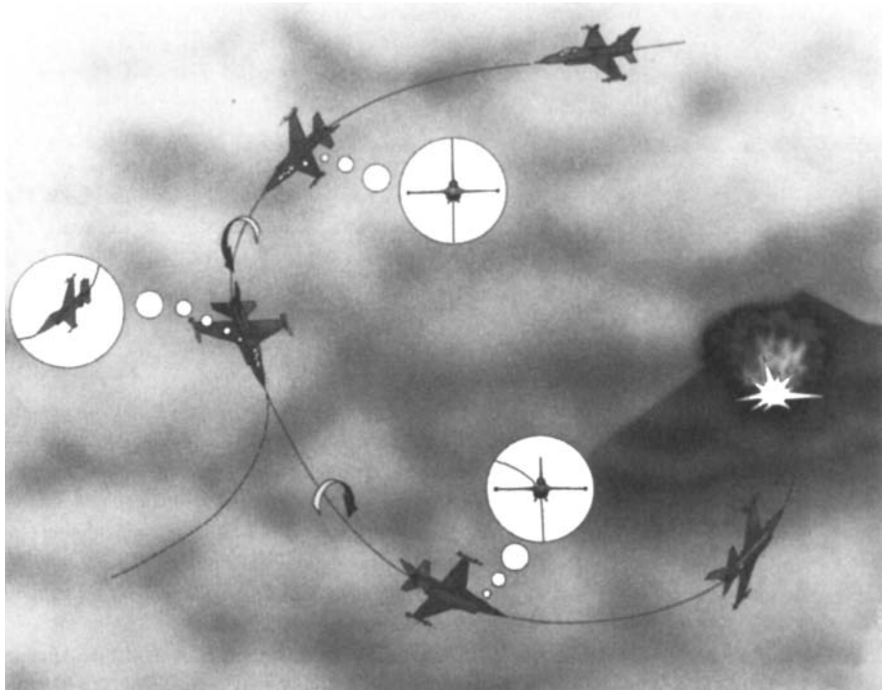


FIGURE 6-29 The graveyard spiral. The pilot in a banked turn loses the sensation of being banked and turning. Upon trying to reestablish a wings-level attitude and stop the turn, the pilot perceives a banked turn in the opposite direction from the original one. Unable to tolerate the sensation of making an inappropriate control input, the pilot banks back into the original turn.

velocity as the head, the cupulae in the ampullae of the horizontal ducts have returned to their resting positions, and the sensation of rotation ceases (Figure 6-30A). If the subject then nods his or her head forward in the pitch plane, let us say a full 90 degrees for the sake of simplicity, they completely remove the horizontal semicircular ducts from the plane of rotation and insert two sets of vertical semicircular ducts into the plane of rotation (Figure 6-30B). The angular momentum of the subject's rotating head is forcibly transferred immediately out of the old plane of rotation, but the angular momentum of the endolymph in the horizontal duct dissipates gradually. Torque resulting from the continuing rotation of the endolymph causes the cupulae in the horizontal ducts to be deviated and a sensation of angular motion occurs in a new plane of the horizontal ducts—now the roll plane relative to the subject's body. Simultaneously, the endolymph in the two sets of vertical semicircular ducts must acquire angular momentum because these ducts have been brought into the plane of constant rotation. The torque required to impart this change in momentum causes deflection of the cupulae in the ampullae of these ducts, and a sensation of angular motion in this plane—the yaw plane relative to the subject's body—results. The combined effect of the cupular deflection in all three sets of the semicircular ducts is a suddenly imposed angular velocity in a plane in which no actual angular acceleration relative to the subject has occurred. In the example given, if the original constant-velocity yaw is to the right and the subject pitches his or her head forward, the resulting Coriolis illusion experienced is a sudden rolling to the left.

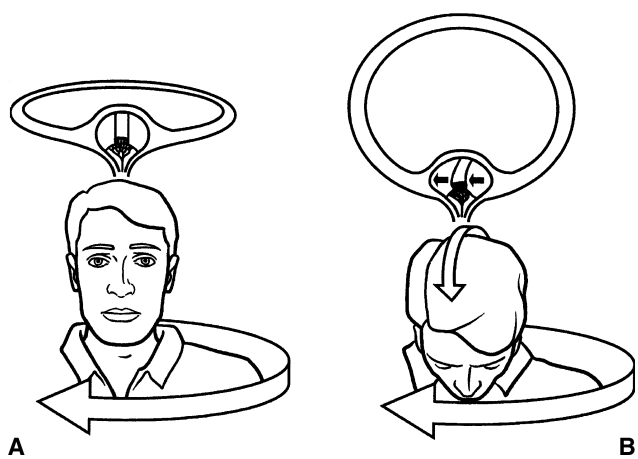


FIGURE 6-30 Mechanism of the Coriolis illusion. A subject rotating in the yaw plane long enough for the endolymph to stabilize in the horizontal semicircular duct (**A**) pitches his head forward and (**B**) angular motion of the endolymph deviates the cupula, causing the subject to perceive rotation in the new plane of the semicircular duct, although no actual rotation occurred in that plane.

A particular perceptual phenomenon experienced occasionally by pilots of relatively high-performance aircraft during instrument flight has been attributed to the Coriolis illusion, because it occurs in conjunction with large movements of the head under conditions of prolonged constant angular velocity. It consists of a sensation of rolling and/or pitching that occurs suddenly after the pilot diverts attention from the front instruments and moves the head to view switches or displays elsewhere (in ergonomically incorrect positions) in the cockpit. This illusion is especially dangerous because it is most likely to occur during an instrument approach, a phase of flight in which altitude is being lost rapidly and cockpit chores (e.g., radio frequency channels) repeatedly require the pilot to break up the instrument cross-check.

Sustained angular velocities associated with instrument flying are insufficient to create Coriolis illusions of any great magnitude. However, the G-excess effect has been proposed to explain the rotation illusion experienced with head movements in flight. So, even if the Coriolis illusion is not responsible for SD in flight, it is a useful tool to demonstrate the fallibility of our nonvisual orientation senses. Nearly every military pilot now living has experienced the Coriolis illusion in the Barany chair or some other rotating device as part of the physiological training, and for most of these pilots it was then they first realized that the orientation senses cannot be trusted; this maybe the most important lesson of all for instrument flying.

Somatogravic Illusion

The otolith organs are responsible for a set of illusions known as *somatogravic illusions*. The mechanism of this type of illusion involves the displacement of otolithic membranes on their maculae by inertial forces that signal a false orientation when the gravitoinertial force is perceived as gravity and therefore vertical. Therefore, a somatogravic illusion can be defined as a false sensation of body tilt resulting from a perception of a nonvertical gravitoinertial force as vertical. The most common example of somatogravic illusions is the illusion of pitching up after taking off into reduced visibility conditions and is perhaps the best illustration of this mechanism.

Consider the pilot of a high-performance aircraft holding his or her position at the end of the runway waiting to take off. Here the only force acting on the otolithic membranes is the force of gravity, and the positions of those membranes on their maculae signal accurately that down is toward the floor of the aircraft. The aircraft now accelerates down the runway, rotates, takes off, cleans up gear and flaps, and maintains a forward acceleration of 1 g until reaching the desired climb speed. The 1 G of inertial force resulting from the acceleration displaces the otolithic membrane toward the back of the pilot's head. The new position of the otolithic membranes is nearly the same as if the pilot had pitched up 45 degrees because the new direction of the resultant gravitoinertial force vector, if one neglects the angle of attack and climb angle, is 45 degrees aft relative to the gravitational vertical (Figure 6-31). Because the sense organs subserving

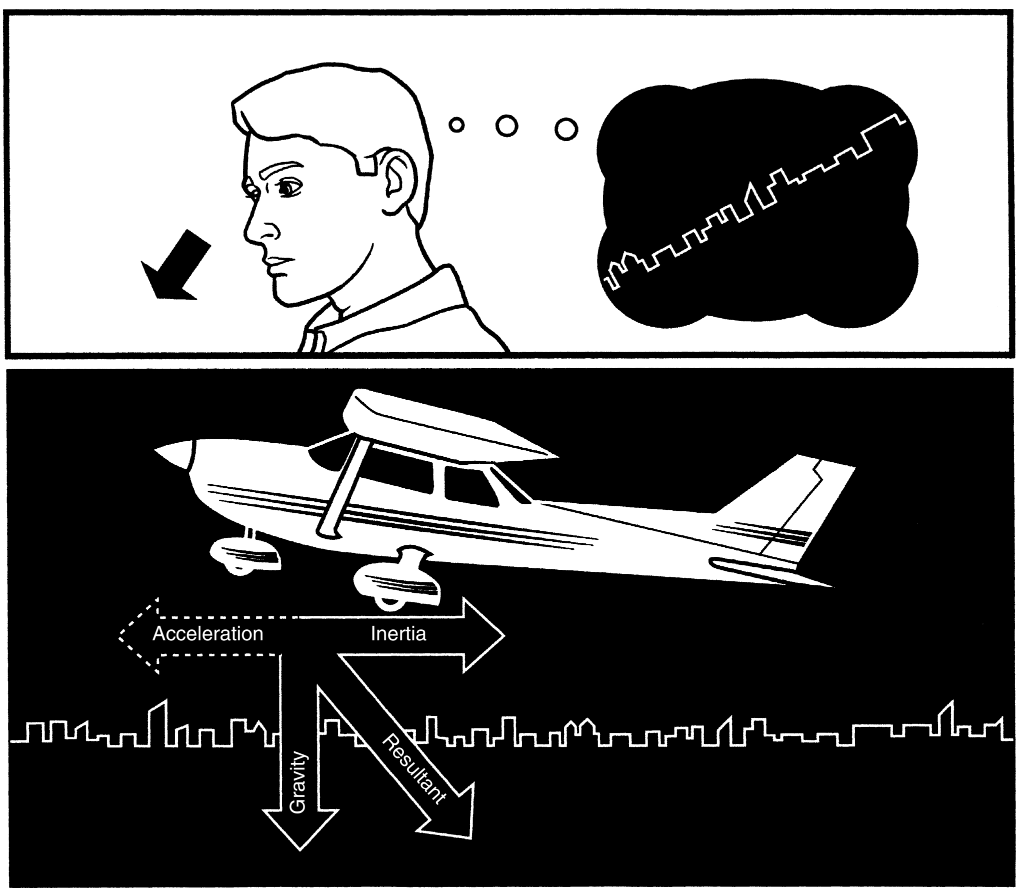


FIGURE 6-31 A somatogravic illusion occurring on takeoff. The inertial force resulting from the forward acceleration combines with the force of gravity to create a resultant gravitoinertial force directed down and aft. The pilot, perceiving down to be in the direction of the resultant gravitoinertial force, feels in an excessively nose-high attitude and is tempted to push the stick forward to correct the illusory nose-high attitude.

perception modalities respond to the direction and intensity of the resultant gravitoinertial force, the pilot's percept of pitch attitude based on the information from his or her otolith organs is one of having pitched up 45 degrees and the information from the pilot's nonvestibular proprioceptive and cutaneous mechanoreceptors senses supports this false percept. Given the very strong sensation of a nose-high pitch attitude, one that is not challenged effectively by the focal visual orientation cues provided by the attitude indicator, the pilot is tempted to push the nose of the aircraft down to cancel the unwanted sensation of flying nose-high. Pilots succumbing to this temptation characteristically crash in a nose-low, wings-level attitude a few miles beyond the end of the runway. Sometimes, however, they are seen descending out of the overcast nose-low and try belatedly to pull up, as though they suddenly regained the correct orientation upon seeing the ground. Pilots of carrier-launched aircraft need to be especially wary of the somatogravic illusion. These pilots experience pulse accelerations lasting 2 to 4 seconds generating peak inertial forces of +3 to +5 G_x. Although the major acceleration is over quickly, the resulting illusion of nose-high pitch can persist for half a minute or more, resulting in a particularly hazardous situation for the pilot who is unaware of this phenomenon (26).

Pilots of high-performance aircraft are not the only pilots that experience a somatogravic illusion of pitching up after takeoff. More than a dozen air transport aircraft are believed to have crashed as a result of the somatogravic illusion occurring on takeoff (27). A relatively slow aircraft, accelerating from 100 to 130 knots over a 10-second period just after takeoff, generates +0.16 G_x on the pilot. Although the resultant gravitoinertial force is only 1.01 G, barely more than the perceptible force of gravity, it is directed 9 degrees aft signifying to the unwary pilot a 9- degree nose-up pitch attitude. Because many slower aircraft climb out at 6 degrees or less, a 9-degree downward pitch correction would put such an aircraft into a descent of 3 degrees or more, the normal final approach slope. In the absence of a distinct visual horizon or, even worse, in the presence of a false visual horizon (e.g., a shoreline) receding under the aircraft and reinforcing the pitch-up vestibular illusion, the pilot's temptation to push the nose down can be overwhelming. This type of illusion has caused mishaps at one particular civil airport so often that a notice has been placed on navigational charts cautioning pilots flying from this airport to be aware of the potential for loss of attitude reference.

The reverse illusion occurs during deceleration, such as lowering flaps for landing. The lowering of the flaps is accompanied by a nose-down pitch change while the angle of attack is stabilizing for the slower airspeed. The naive pilot, typically a student, may panic due to the misperception of the aircraft nosing over into a dive.

Although the classic graveyard spiral was indicated earlier to be a consequence of a pilot experiencing a somatogyral illusion, it may also be the result of a somatogravic illusion. A pilot who is flying "by the seat of the pants" applies the necessary control inputs to create a resultant G-force vector having the same magnitude and direction as that which his or her desired flight path would create. Unfortunately, any particular G vector is not unique to one particular condition of aircraft attitude and motion, and the likelihood that the G vector created by a pilot flying in this mode corresponds for more than a few seconds to the flight condition desired is remote indeed. Specifically, once an aircraft has departed a desired wings-level attitude because of an unperceived roll and the pilot does not correct the resulting bank, the only way the pilot can create a G vector that matches the G vector of the straight and level conditions is with a descending spiral. In this condition, as is always the case in a coordinated turn, the centrifugal force resulting from the turn provides a G_y force that cancels the $-G_y$ component of the force of gravity that exists when the aircraft is banked. In addition, the tangential linear acceleration associated with the increasing airspeed resulting from the dive provides a $+G_x$ force that cancels the $-G_x$ component of the gravity vector that exists when the nose of the aircraft is pointed downward. Although the vector analysis of the forces involved in the graveyard spiral may be somewhat complicated, a skilled pilot can easily manipulate the stick and rudder pedals to cancel all vestibular and other nonvisual sensory indications that result from the aircraft turning and diving. In one mishap involving a dark-night takeoff of a commercial airliner, the recorded flight data indicated that the resultant G force, which the pilot created by his control inputs allowed him to perceive his desired 10- to 12-degree climb angle and a net G force between 0.9 and 1.1 G for virtually the whole flight, although he actually leveled off and then descended in an accelerating spiral until the aircraft crashed nearly inverted.

Inversion Illusion

The inversion illusion is a type of somatogravic illusion in which the resultant gravitoinertial force vector rotates backward with respect to the seat of the pilot. It will end up pointing away from rather than toward the Earth's surface, resulting in the pilot experiencing the sensation that he and/or she is upside down. Figure 6-32 demonstrates how this type of illusion can occur (28). Typically, a steep climbing high-performance aircraft levels off more or less abruptly at the desired altitude. This maneuver subjects the aircraft and pilot to a $-G_z$ centrifugal force, resulting from the arc flown just before leveling off. Simultaneously, as the aircraft changes to a more level attitude airspeed picks up rapidly adding a $+G_x$ tangential inertial force to the overall force environment. Adding the $-G_z$ centrifugal force and the $+G_x$ tangential force to the 1-G gravitational force results in a net gravitoinertial force vector that rotates backward and upward relative to the pilot. This stimulates the pilot's otolith organs in a manner similar to the way a pitch upward into an inverted position would. Semicircular ducts should respond to the actual pitch downward but for some reason this conflict is resolved in favor of the otolith-organ information, perhaps because the semicircular-duct response is transient while the otolith-organ responses persists, or perhaps because the information from the other mechanoreceptors reinforce

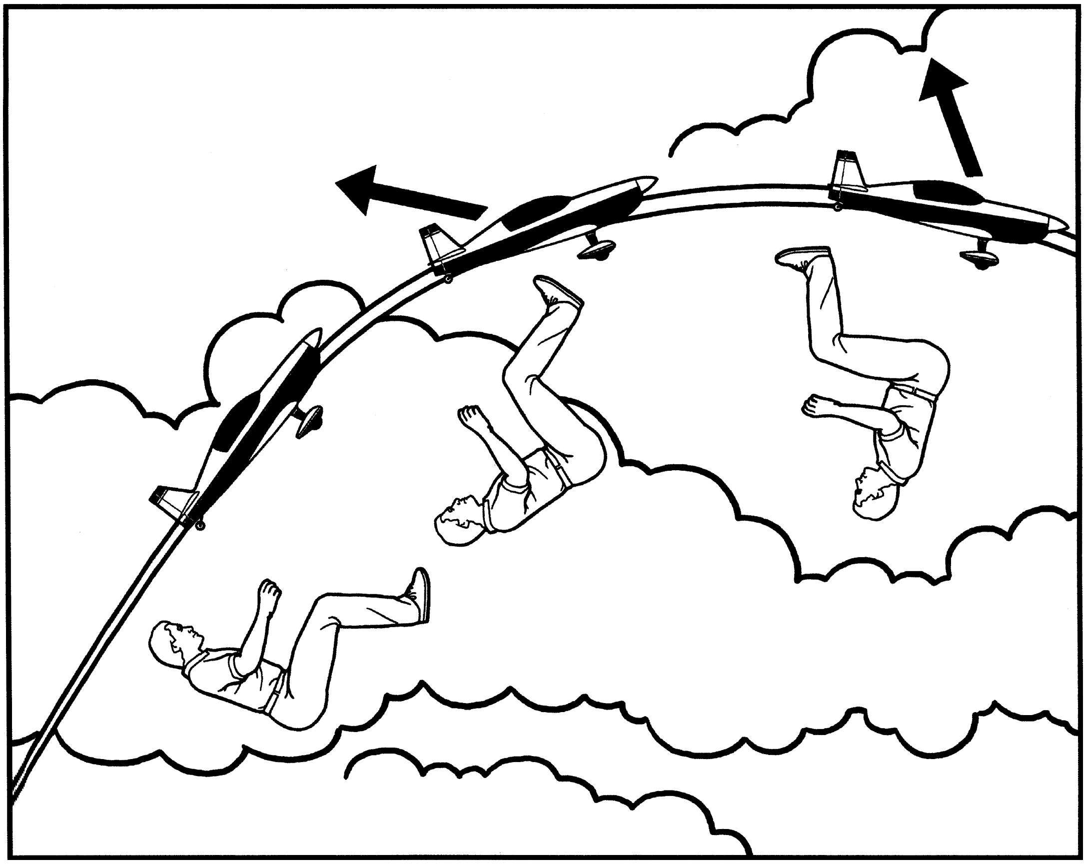


FIGURE 6-32 The inversion illusion. Centrifugal and tangential inertial forces during a level-off combine with the force of gravity to produce a resultant gravitoinertial force that rotates backward and upward with respect to the pilot, causing a perception of suddenly being upside down. Turbulent weather can produce additional inertial forces that contribute to the illusion. (Adapted from Martin JF, Jones GM. Theoretical man-machine interaction which might lead to loss of aircraft control. *Aerosp Med* 1965;36:713–716.)

the information from the otolith organs. The pilot who responds to the inversion illusion by pushing forward on the stick to counter the perceived pitching up and over backward prolongs the illusion by creating more $-G_z$ and $+G_x$ forces, thereby aggravating the situation. Turbulent weather usually contributes to the development of the illusion; certainly, downdrafts are a source of $-G_z$ forces that can add to the net gravitoinertial forces producing the inversion illusion. Again, fighter jet pilots are not the only ones to experience this illusion. Several reports of the inversion illusion involve crew of large airliners who lost control of aircraft because the pilot lowered the nose inappropriately after experiencing the illusion. Jet upset is the name for the sequence of events that includes instrument weather, turbulence, the inability of the pilot to read his or her instruments, the inversion illusion, a pitch-down control input, and difficulty recovering the aircraft because of resulting aerodynamic or mechanical forces (29).

G-Excess Effect

The G-excess effect results from a change in G magnitude, whereas somatogravic illusions result from a change in the direction of the net G force. The G-excess effect is a false or exaggerated sensation of body tilt that can occur when the G environment is sustained at greater than 1 G. For a simplistic illustration of this phenomenon, let us imagine a subject sitting upright in a $+1G_z$ environment tipping the head forward 30 degrees (Figure 6-33). As a result of this change in head position, the subject's otolithic membranes slide forward the appropriate amount for a 30-degree tilt relative to vertical. Now suppose that the same subject is sitting upright in a $+2G_z$ environment and again tips the head 30 degrees forward. This time, the subject's otolithic membranes slide forward more than the previous situation because of the doubled gravitoinertial force acting on them. The displacement of the otolithic membranes now corresponds not to a 30-degree forward tilt in the normal 1-G environment but to a much greater tilt, theoretically as much as 90 degrees (2 sin 30 degrees = sin 90 degrees). The subject, however, initiated only a 30-degree head tilt and expects to perceive no more than that. The unexpected perceived tilt is therefore referred to the immediate environment, that is, the subject perceives his or her vehicle to have tilted by the amount equal to the difference between the actual and

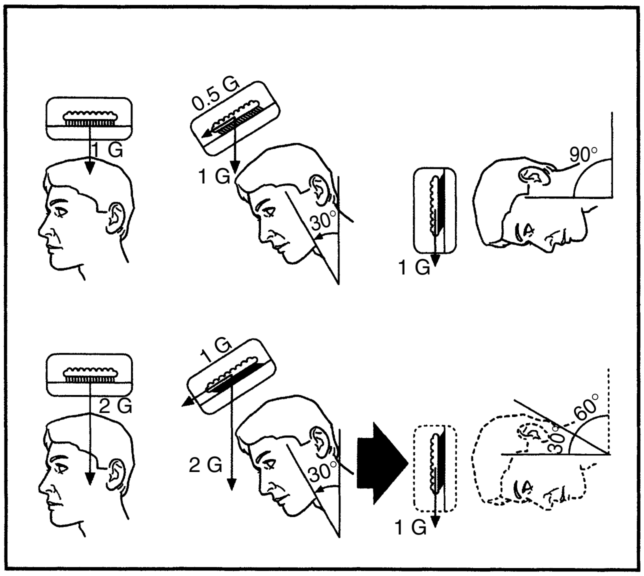


FIGURE 6-33 Mechanism of the G-excess illusion. The subject in a 1-G environment (*upper half* of figure) experiences the result of a 0.05-G pull on his utricular otolithic membranes when the head is tilted 30 degrees off the vertical, and the result of a 1-G pull when the head is tilted a full 90 degrees. The subject in a 2-G environment (*lower half* of figure) experiences the result of a 1-G pull when upon tilting the head only 30 degrees. The illusory tilt perceived by the subject is attributed to external forces (*lower right*).

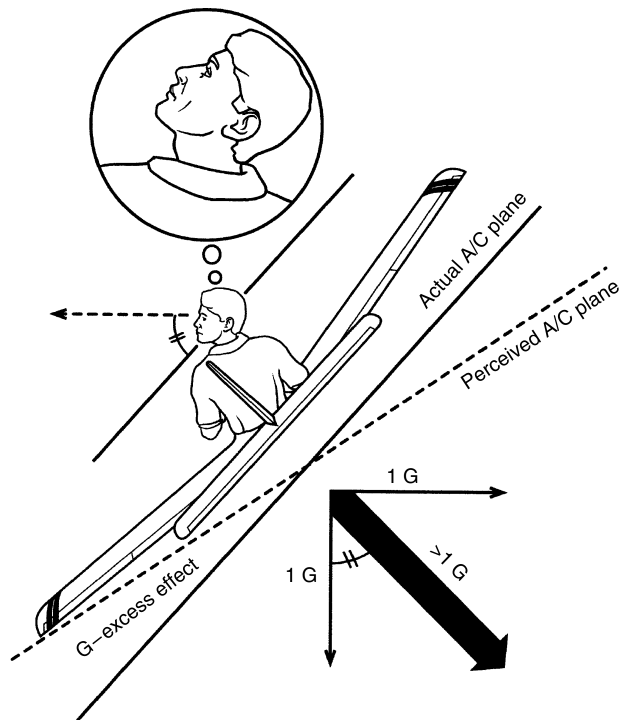


FIGURE 6-34 The G-excess illusion during a turn in flight. G-induced excessive movement of the pilot's otolithic membranes causes the pilot to feel an extra amount of head and body tilt, which is interpreted as an underbank of the aircraft when the pilot looks up to the inside of the turn. Correcting for the illusion, the pilot overbanks the aircraft and it descends.

expected percepts of tilt. The actual perceptual mechanism underlying the G-excess effect is more complicated than this illustration suggests. First, the plane of the utricular maculae is not really horizontal but slopes upward 20 to 30 degrees from back to front; second, the saccular maculae contribute in an undetermined manner to the net percept of tilt; and third, as is usually the case with vestibular illusions, good visual orientational cues tend to attenuate the illusory percept. However, experimental evidence clearly demonstrates the existence of the G-excess effect. Perceptual errors of 10 to 20 degrees are generated at 2 G, and errors are approximately half that amount at 1.5 G (30,31).

In fast-moving aircraft, the G-excess illusion can occur as a result of the moderate amount of G force pulled in a penetration turn or procedure turn, for example. If the pilot has to look down and to the side to select a new radio frequency or to pick up a dropped pencil while in a turn, he or she should experience an uncommanded tilt in both pitch and roll planes due to the G-excess illusion. As noted previously, the G-excess illusion may be responsible for the false sensation of pitch and/or roll generally attributed to the Coriolis illusion under such circumstances. The G excess has been suspect in several mishaps involving fighter/attack aircraft making 2 to 5.5 g turns at low altitudes in conditions of essentially good visibility. For some reason, the aircraft were overbanked while the pilots were looking out of the cockpit for an adversary, wingman, or some other object, and as a result descended into the terrain (32,33).

The theory is that the G-excess effect causes the pilot to have an illusion of underbank when the head is either facing the inside of the turn and elevated (Figure 6-34) or facing the outside of the turn and depressed. When facing forward, the pilot would have an illusion of pitching up (i.e., climbing) during the turn (34).

Therefore, in any of these common circumstances if the pilot does not maintain a continuous visual reference to the Earth's surface, he or she would likely cause the aircraft to descend in response to the illusory change of attitude caused by the G-excess effect. Perhaps in some of the mishaps mentioned, the pilot's view of the spatial environment was inadequate because he or she had been looking at sky rather than ground, or perhaps G-induced tunnel vision was responsible for loss of ambient visual cues. In any case, it is apparent that the pilots in these scenarios failed to perceive attitude, vertical velocity, and height above the ground correctly, that is, they were spatially disoriented.

The elevator illusion is a special kind of G-excess effect. Because of the way the utricular membranes are variably displaced with respect to their maculae by increases and decreases in $+G_z$ force, false sensations of pitch and vertical velocity can result even when the head remains in the normal upright position. When an upward acceleration (as occurs in an elevator) causes the net G_z force to increase, a sensation of climbing and tilting backward can occur. In flight, such an upward acceleration occurs when an aircraft levels off from a sustained descent. This temporary increase in $+G_z$ loading may induce the sensation of a pitch up and climb in a pilot if his or her view of the outside world is restricted by night, weather, or head-down cockpit chores. Compensating for the illusory pitch-up sensation, the pilot would likely put the aircraft back into a descent, all the while feeling that the aircraft is maintaining a constant altitude. In one in-flight study of the elevator illusion, blindfolded pilots were told to maintain perceived level flight after a relatively brisk level-off from a sustained 10 m/s (2,000-ft/min) descent. The mean response of the six pilots was a 6.6 m/s (1,300-ft/min) descent (35,36). Clearly this tendency to re-establish a descent is especially dangerous during the final stage of a non–precision instrument approach at night or in weather. Upon leveling off at the published minimum descent altitude, the pilot typically starts a visual search for the runway. If the pilot fails to monitor the flight instruments during this critical time, the elevator illusion can cause him or her to unwittingly put the aircraft into a descent and thereby squander the altitude buffer protecting the aircraft from ground impact.

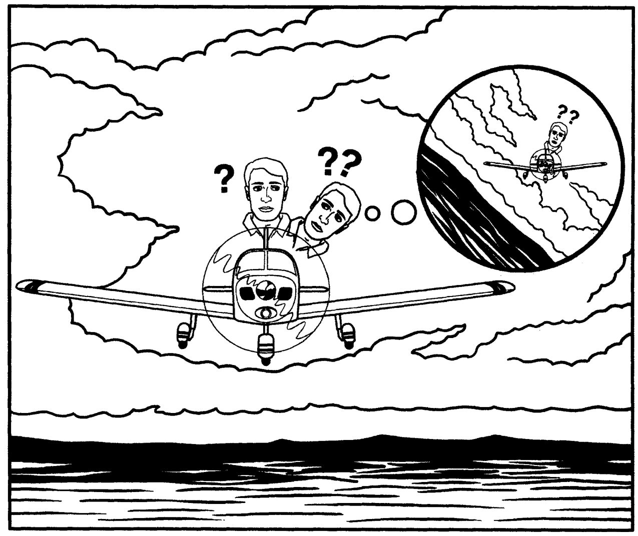


FIGURE 6-35 The leans, the most common of all vestibular illusions in flight. Falsely perceiving oneself to be in a right bank, but flying the aircraft straight and level by means of the flight instruments, this pilot leans to the left in an attempt to assume an upright posture compatible with the illusion of bank.

Oculogravic Illusion

An oculogravic illusion can be thought of as a visual correlate of the somatogravic illusion and occurs under the same stimulus conditions. A pilot who is subjected to deceleration resulting from the application of speed brakes, for example, experiences a nose-down pitch because of the somatogravic illusion. Simultaneously, the pilot observes the front instrument panel to move downward, confirming the sensation of tilting forward. The oculogravic illusion is therefore the visually apparent movement of an object that is actually in a fixed position relative to the subject during a change in direction of the net gravitoinertial force. Like the oculogyral illusion, the oculogravic illusion probably results from the attempt to maintain visual fixation during a vestibulo-ocular reflex, elicited in this case by the change in direction of the applied G vector rather than by angular acceleration.

The Leans

By far the most common vestibular illusion in flight is the leans (37). Virtually every instrument-rated pilot has had or will have the leans in one form or another at some time during his or her flying career. The leans consists of a false percept of angular displacement about the roll axis and is, therefore, an illusion of bank which is frequently associated with a vestibulospinal reflex, appropriate to the false percept, that results in the pilot actually leaning in the direction of the falsely perceived vertical (Figure 6-35). The usual explanations of the leans invoke the known deficiencies of both otolith-organ and semicircular-duct sensory mechanisms. As indicated previously, the otolith organs are not reliable sources of information about the exact direction of the true vertical because they respond to the resultant gravitoinertial force, not to gravity alone. Furthermore, other sensory inputs can sometimes override otolith-organ cues and result in a false perception of the vertical, even when the gravitoinertial force experienced is truly vertical. The semicircular ducts can provide such false inputs in flight by responding accurately to some roll stimuli but not responding to others due to being below the threshold. If, for example, a pilot is subjected to an angular acceleration during a roll so that the product of the acceleration and its time of application do not reach a threshold value, say 2 degrees/s, the pilot will not perceive the roll. Suppose the pilot, who is trying to fly straight and level, is subjected to an unrecognized and uncorrected 1.5-degree/s roll for 10 seconds, a 15-degree bank results. If the pilot then notices the unwanted bank and corrects it by rolling the aircraft back upright with a suprathreshold roll rate, say 15 degrees/s, only half of the actual roll motion that took place, the half resulting from the correction, is experienced. Because the pilot started from a wings-level position, he or she is left with the illusion of having rolled into a 15-degree bank in the direction of the correction roll, although the aircraft is again wings-level. At this point, the pilot has the leans and may be able to fly the aircraft properly by use of the good instrument training practices known as the *instrument cross-check*. At times the pilot may find the task difficult, but forcing the attitude indicator to read correctly is often the only known countermeasure. This illusion can last for many minutes, seriously degrading the pilot's flying efficiency during that time.

Interestingly, pilots frequently get the leans after prolonged turning maneuvers that do not supply alternating subthreshold and suprathreshold angular motion stimuli. In a holding pattern, for example, the pilot rolls into a 3-degree/s standard-rate turn, holds the turn for 1 minute, rolls out and flies straight and level for 1 minute, turns again for 1 minute, and so on until traffic conditions permit him or her to proceed toward the destination. During the turning segments, the pilot initially feels the roll into the turn and accurately perceives the banked attitude. But as the turn continues, the percept of being in a banked turn dissipates and is replaced by a feeling of flying straight and level, both because the sensation of turning is lost when the endolymph comes up to speed in the semicircular ducts (somatogyral illusion) and because the net G force being directed toward the floor of the aircraft provides a false cue of verticality (somatogravic illusion). Then when the pilot rolls out of the turn, he or she feels a roll into a banked turn in the opposite direction. With experience, a pilot learns to suppress these false sensations by paying strict attention to the attitude indicator. Unfortunately, when particularly busy the pilot cannot dispel the illusion. The leans may also be caused by misleading peripheral visual orientation cues, as mentioned in the section **Visual Illusions**. Roll angular vection is particularly effective in this regard, at least in the laboratory. One thing about the leans is apparent: there is no single explanation of this illusion. The deficiencies of several orientation-sensing systems in some cases reinforce each other to create an illusion; in other cases, the inaccurate information from one sensory modality for some reason is selected over the accurate information from others to create the illusion. Stories have surfaced of pilots suddenly experiencing the leans for no apparent reason at all or even of experiencing it voluntarily by imagining the Earth to be in a different direction from the aircraft. The point is that one must not think that the leans illusion, or any other illusion for that matter, occurs as a totally predictable response to a physical stimulus. There is much more to perception than stimulation of the end organs.

Disorientation

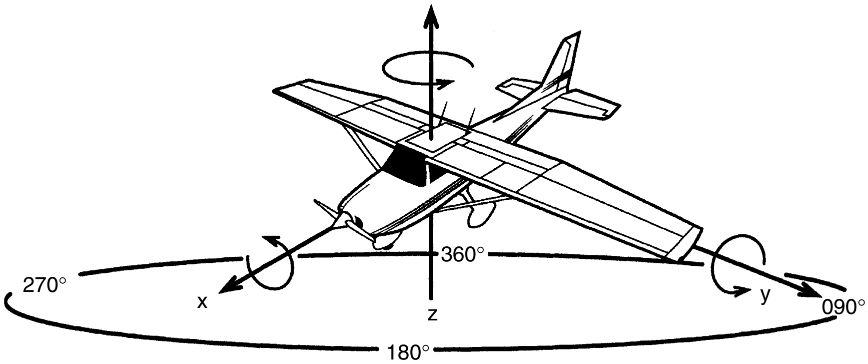
Definitions

An orientational percept is a sense of one's position and motion relative to the plane of the Earth's surface. It can be primary (i.e., natural), meaning that it is based on ambient visual, vestibular, or other sensations that normally contribute to our orientation in our natural environment; or it can be secondary (i.e., synthetic), meaning that it is intellectually constructed from focal visual, verbal, or other symbolic data, such as that presented by flight instruments. Although the former type of orientational percept is essentially irrational (not subject to analysis and interpretation) and involves largely preconscious mental processing, the latter type is rational and entirely conscious. A locational percept, to be distinguished from an orientational percept, is a sense of one's motion and position in (as opposed to relative to) the plane of the Earth's surface. An accurate locational percept is achieved by reading a map or knowing the latitude and longitude of one's location.

SD is a state characterized by an erroneous orientational percept, that is, an erroneous sense of one's position and motion relative to the plane of the Earth's surface. Geographic disorientation, or "being lost," is a state characterized by an erroneous locational percept. These definitions together encompass all the possible positions and velocities, both translational and rotational, along and about three orthogonal Earth-referenced axes. Spatial orientation information includes those parameters that an individual on or near the Earth's surface with eyes open can reasonably be expected to process accurately on a sunny day. Lateral tilt, forward-backward tilt, angular position about a vertical axis, and their corresponding first derivatives with respect to time are the angular positions and motions including height above ground, forward-backward velocity, sideways velocity, and up-down velocity. Absent from this collection of spatial orientation information parameters are the location coordinates, linear position dimensions in the horizontal plane. In flight, orientation information is described in terms of flight instrument-based parameters (Figure 6-36). Angular position is bank, pitch, and heading and the corresponding angular velocities are roll rate, pitch rate, and turn rate (or yaw rate). The linear position parameter is altitude and the linear velocity parameters are airspeed (or groundspeed), slip/skid rate, and vertical velocity. In-flight navigation information comprises linear position dimensions in the horizontal plane, such as latitude and longitude or bearing, and distance from a navigation reference point.

Air Force Instruction 11-217, Vol 1, Instrument Flight Procedures (38), categorizes flight instruments into three functional groups: control, performance, and navigation. In the control category are the parameters of aircraft attitude (i.e., pitch and bank) and engine power or thrust. In the performance category are airspeed, altitude, vertical velocity, heading, turn rate, slip/skid rate, angle of attack, acceleration (G loading), and flight path (velocity vector). The navigation category includes course, bearing, range, latitude/longitude, time, and similar parameters useful for determining location on the Earth's surface. This categorization of flight instrument parameters allows us to construct a useful operational definition of SD: an erroneous sense of any flight parameters displayed by aircraft control and performance instruments. Geographic disorientation, in contrast, is therefore an erroneous sense of any of the flight parameters displayed by aircraft navigation instruments. The practical utility of these operational definitions is that they establish a common understanding of what is meant by SD among all parties investigating an aircraft mishap, whether they are pilots, flight surgeons, aerospace physiologists, or experts in some other discipline. If the answer to the question, "Did the pilot not realize the actual pitch attitude and vertical velocity (and/or other control or performance parameters)?" is "Yes," then it is obvious that the pilot was spatially disoriented, and the contribution of the disorientation to the sequence of events leading to the mishap is clarified.

Aircrew tend to be imprecise when they discuss SD, preferring to say that they "lost situational awareness" rather than "became disoriented," as though having experienced SD stigmatizes them. Situational awareness involves a correct appreciation of a host of conditions, including the tactical environment, location, weather, weapons capability, mental capabilities, administrative constraints, as well as spatial orientation. Therefore, if the situation about which a pilot



	Angular		Linear	
Axis	Position	Velocity	Position	Velocity
x	Bank	Roll rate	*	Airspeed
y	Pitch	Pitch rate	*	Slip/skid rate
z	Heading	Turn rate	Altitude	Vertical velocity

* Navigation information

FIGURE 6-36 Flight instrument–based parameters of spatial orientation. Spatial disorientation is a state characterized by an erroneous sense of any of these parameters.

lacks awareness is his or her position and motion relative to the plane of the Earth's surface, then that pilot has SD, specifically, as well as loss of situational awareness, generally.

Types of Spatial Disorientation

We distinguish three types of SD in flight: Type I (unrecognized), Type II (recognized), and Type III (incapacitating). In Type I disorientation, the pilot does not consciously perceive any manifestations of disorientation. He or she experiences no disparity between natural and synthetic orientational percepts, has no suspicion that a flight instrument (e.g., attitude indicator) has malfunctioned, and does not feel that the aircraft is responding incorrectly to his or her control inputs. In unrecognized SD the pilot is oblivious to the fact that he or she is disoriented, and controls the aircraft completely in accord with and in response to a false orientational percept. To distinguish Type I disorientation from the others, and to emphasize its insidiousness, some pilots and aerospace physiologists call Type I SD as "misorientation."

In Type II disorientation, the pilot consciously perceives some manifestation of disorientation. The pilot may experience a conflict between what he or she feels the aircraft is doing and what the flight instruments indicate that it is doing. Alternatively, the pilot may not experience a genuine conflict, but merely conclude that the flight instruments are faulty. The pilot may also feel that the aircraft is attempting to assume a pitch or bank attitude other than the one he or she is trying to establish. Type II disorientation is what pilots are referring to when they use the term *vertigo*, as in "I had a bad case of vertigo on final approach." Although Type II SD is labeled "recognized," this does not mean that the pilot must necessarily realize he or she is disoriented. The pilot may only realize that there is a problem controlling the aircraft, not knowing that the source of the problem is SD.

With Type III SD the pilot experiences an overwhelming, incapacitating physiologic response to physical or emotional stimuli associated with the disorientation event. Pilots may have vestibular nystagmus to such a degree that they can neither read the flight instruments nor obtain a stable view of the outside world, vestibulo-ocular disorganization. Or they may have such strong vestibulospinal reflexes that they cannot control the aircraft. Pilots may even be so incapacitated by fear that they are unable to make a rational decision and may freeze on the controls. The important feature of Type III SD is that the pilot is disoriented and most likely knows it, but cannot do anything about it.

Examples of Disorientation

The last of four F-15 Eagle fighter aircraft took off on a daytime sortie in bad weather, intending to follow the other three in a radar in-trail departure. Because of a navigational error committed by the pilot shortly after takeoff, he was unable to find the other aircraft on his radar. Frustrated, the pilot elected to intercept the other aircraft where he knew they would be in the arc of the standard instrument departure, so he made a beeline for that point, presumably scanning his radar diligently for the blips he knew should be appearing at any time. Meanwhile, after ascending to 1,200 m (4,000 ft) above ground level, he entered a descent of approximately 750 m/min (2,500 ft/min) or 13 m/s as a result of an unrecognized 3-degree nose-low attitude. After receiving requested position information from another member of the flight, the pilot either suddenly realized he was in danger of colliding with another aircraft or he suddenly found the other aircraft on the radar because he then made a steeply banked turn, either to avoid a perceived threat of collision or to join up with the rest of the flight. Unfortunately, he had by this time descended far below the other aircraft and was going too fast to avoid the ground, which became visible under the overcast just before the aircraft crashed (39).

This mishap resulted from an episode of unrecognized, or Type I, disorientation. The specific illusion responsible appears to have been the somatogravic illusion, which was created by the forward acceleration of this high-performance aircraft during takeoff and climb-out. The pilot's preoccupation with the radar task compromised his instrument scan to the point where false vestibular cues were able to penetrate his orientational information processing. Having unknowingly accepted an inaccurate orientational percept, he controlled the aircraft accordingly until it was too late to recover.

Examples of recognized, or Type II, SD are easier to obtain than examples of Type I because most experienced pilots have anecdotes about how they "got vertigo" and fought it off. Some pilots were not so fortunate, however. One F-15 Eagle pilot, after climbing his aircraft in formation with another F-15 at night, began to experience difficulty in maintaining spatial orientation and aircraft control upon leveling off in the clouds at 8,200 m (27,000 ft). "Talk about practice bleeding," he commented to the lead pilot. Having decided to go to another area because of the weather, the two pilots began a descending right turn. At this point, the pilot on the wing told the lead pilot, "I'm flying upside down." Shortly afterward, the wingman considered separating from the formation, saying, "I'm going lost wingman." Then he said, "No, I've got you," and finally, "No, I'm going lost wingman." The hapless wingman then caused his aircraft to descend in a wide spiral and crashed into the desert less than 1 minute later, although the lead pilot advised the wingman several times during the descent to level out. In this mishap, the pilot probably had an inversion illusion upon leveling off in the weather, and entered a graveyard spiral after leaving the formation. Although he knew he was disoriented, or at least recognized the possibility, he still was unable to control the aircraft effectively (39).

That fact that a pilot can realize he is disoriented, see accurate orientation information displayed on the attitude indicator, and still fly into the ground always strains the credulity of nonaviators. Pilots who have had SD, who have experienced fighting oneself for control of an aircraft, are less skeptical.

The pilot of an F-15 Eagle, engaged in vigorous air combat tactics training with two other F-15s on a clear day, initiated a hard left turn at 5,200 m (17,000 ft) above ground level. For reasons that have not been established with certainty, his aircraft began to roll to the left at a rate estimated at 150 to 180 degrees/s. He transmitted, "out-of-control autoroll," as he descended through 4,600 m (15,000 ft). The pilot made at least one successful attempt to stop the roll, as evidenced by the momentary cessation of the roll at 2,400 m (8,000 ft), then the aircraft began to roll again to the left. Forty seconds elapsed between the time that the rolling began and the time that the pilot ejected but it was too late. Regardless of whether the rolling was caused by a mechanical malfunction or was an autoroll induced by the pilot, the likely result of his extreme motion was vestibulo-ocular disorganization, which not only prevented the pilot from reading his instruments but also kept him from orienting with the natural horizon. Therefore, Type III disorientation probably prevented him from taking appropriate corrective action to stop the roll and maintain level flight; if not that, it certainly compromised his ability to assess accurately the deterioration of his situation.

Statistics

The fraction of aircraft mishaps caused by or contributed to by SD has doubled over the five decades between 1950 and 2000. The National Transportation Safety Board identified 125 aircraft accidents between 2000 and 2006 where SD was the primary factor and that continuing efforts to educate pilots about SD and the hazard it represents have been to no avail. Fortunately, the total number of major mishaps and the number of major mishaps per million flying hours have dropped considerably over the same period (at least in the United States), so it appears that such flying safety educational efforts actually have been effective. A number of statistical studies of SD mishaps in the USAF and other organizations will provide an appreciation of the magnitude of the problem in aviation (40–42).

In 1956, Nuttall and Sanford (43) reported that, in one major air command during the period of 1954 to 1956, SD was responsible for 4% of all major aircraft mishaps and 14% of all fatal aircraft mishaps. In 1969, Moser (44) reported a study of aircraft mishaps in another major air command during the 4-year period from 1964 to 1967: he found that SD was a significant factor in 9% of major mishaps and 26% of fatal mishaps. In 1971, Barnum and Bonner (45) reviewed the Air Force mishap data from 1958 through 1968 and found that in 281 (6% of the 4,679 major mishaps) SD was a causative factor; fatalities occurred in 211 of those 281 accidents, accounting for 15% of the 1,462 fatal mishaps. A comment by Barnum and Bonner summarizes some interesting data about the "average pilot" involved in an SD mishap: "He will be around 30 years of age, have 10 years in the cockpit, and have 1500 hours of first pilot/instructor-pilot time. He will be a fighter pilot and will have flown approximately 25 times in the 3 months before his accident." In an independent 1973 study, Kellogg (46) found the relative incidence of SD mishaps in the years 1968 through 1972 to range from 4.8% to 6.2% and confirmed the high proportion of fatalities in mishaps resulting from SD.

The U. S. Air Force experiences the largest number of SD losses of any reporting entity. Losses were particularly severe with the high-performance fighters, F-15 and F-16. From 1975 to 1993, of the 204 USAF F-16s lost 30% were due to SD. This was a rate of 5.09 accidents per 100,000 flight hours (47). The cost of the Air Force aircraft destroyed each year in disorientation mishaps until the decade of the 1980s was on the order of $50 million/yr. From 1980 through 1989, more than half a billion dollars worth of Air Force resources were lost as a result of SD. During this decade the average dollar cost of SD to the Air Force was on the order of $150 to 200 million but occasional losses of particularly expensive aircraft result in much higher figures in some years (48). More recent studies have shown that the total number of SD-related accidents has decreased but the average cost of an Air Force accident has increased (42).

SD accidents are common throughout the world. From 1982 to 1992, the Canadian forces experienced 14 SD accidents with 24 fatalities representing 23% of all aircraft accidents (49). The Indian Air Force and Royal Air Force experienced similar problems and had similar statistics (50).

Rotary wing aircraft do not escape SD. One of the authors (A.J. Parmet) has noted a particular sensitivity to the leans during instrument operations in helicopters. Night operations, particularly when using night-vision devices that markedly restrict peripheral vision accounted for 43% of U.S. Army SD accidents during 1987 to 1995 (51). Panoramic night-vision goggles are being developed, which promise to greatly reduce this problem (52).

The conventional wisdom is that more than half of the mishaps associated with SD involve Type I, most of the remainder involve Type II, and very few involve Type III. The same wisdom suggests that the source of the disorientation is visual illusions in approximately half of the mishaps, and vestibular/somatosensory illusions in the other half, with combined visual and vestibular illusions accounting for at least some of the mishaps. An analysis of Air Force aircraft mishaps in 1988 in which SD was suspected, by the investigating flight surgeon, revealed that all involved Type I disorientation; two apparently resulted from visual illusions, three from vestibular illusions, and three from mixed visual and vestibular illusions (53). For this particular year, the distribution across the three categories (visual, vestibular, and mixed) did not reflect the conventional thinking.

The experience of the U.S. Navy with SD is also instructive (54). During the years 1980 through 1989, a total of 112 Class A flight mishaps involved SD as a definite, probable, or possible causal factor. Of the 40 mishaps in the "definite" category, 20 occurred in daytime and 20 happened at night; 17 occurred during flight over land, and 23 were over water. Thirty-two aircraft, including 15 fighter/attack aircraft; 6 training aircraft; and 11 helicopters, were destroyed; and 38 lives were lost in the 13 fatal mishaps out of 40 Class A mishaps. The mean experience level for the Navy pilots involved in SD mishaps was 1,488 hours (median: 1,152 hours), approximately the same as that for Air Force pilots. Surprisingly, the incidence of SD-related mishaps for the U.S. Air Force, Navy, and Army have been remarkably similar over the years, although the flying missions of those military services are somewhat different. Comparison with other national services finds that there is general agreement among all aircraft operators.

One problem with the mishap statistics presented earlier is that they are conservative, representing only those mishaps in which disorientation was stated to be a definite, possible, or probable factor by the Safety Investigation Board. In actuality, many mishaps resulting from SD were not identified as such because other factors such as distractions, task saturation, and poor crew coordination initiated the chain of events resulting in the mishap. These other factors were considered more relevant or more amenable to correction than the disorientation that followed and ultimately caused the pilot to fly the aircraft into the ground or water. In the Air Force from 1980 through 1989, a total of 263 mishaps and 425 fatalities, at a cost of more than $2 billion, resulted from "loss of situational awareness" (Freeman JE; *personal communication* to Kent Gillingham and co-author WE, 1990). It is apparent that the great majority of those mishaps would not have happened if the pilots had at all times correctly assessed their pitch/bank attitude, vertical velocity, and altitude, that is, if they had not been spatially disoriented. Therefore, we can infer that SD causes considerably more aircraft mishaps than the disorientation-specific statistics would lead us to believe, probably two or three times as many.

Worldwide, SD is the leading cause of commercial aircraft accidents, closely followed by controlled flight into terrain (CFIT). CFIT, where there is a loss of situational awareness, adds to the death totals and is clearly a variation of SD. CFIT occurs when an airworthy aircraft under the control of the pilot is flown into terrain or obstacles with inadequate awareness by the pilot of the impending disaster (28,40,55).

Air-carrier mishaps caused by SD are infrequent but do occur. Fourteen such mishaps occurring between 1950 and 1969 were reportedly due to somatogravic and visual illusions that resulted in the so-called dark-night takeoff accident (29). In addition, 26 commercial airliners were involved in jet-upset incidents or accidents during the same period (32). From 1987 to 1999, there were 4 commercial SD accidents in the United States with 482 fatalities. Worldwide, excluding the United States, there were 38 commercial airliner accidents with 2,280 fatalities. Loss of situational awareness leading to CFIT caused 11 accidents with 2,280 fatalities in the United States and 36 accidents with 2,334 fatalities worldwide during the same period. All other causes of accidents, including terrorism, accounted for 18 accidents in the United States with 791 deaths and 61 accidents worldwide with 3,904 deaths (56). SD is a problem in general (nonmilitary, non–air carrier) aviation. Kirkham et al (57). reported in 1978 that although SD was a cause or factor in only 2.5% of all general aviation aircraft accidents in the United States, it was the third most common cause of fatal general aviation accidents. Of the 4,012 fatal general aviation mishaps occurring in the years 1970 through 1975, 627 (15.6%) involved SD as a cause or factor. The U.S. National Transportation Safety Board recorded civil aviation events during the period 1990 to 1998 with a total of 16,500 SD accidents, almost all of these occurring in general aviation aircraft. Of these, 1,407 were CFIT and of those, 90% were fatal (58). CFIT accidents continue to increase in general aviation while declining in commercial operations due to improved training and equipment (55,59).

Dynamics of Spatial Orientation and Disorientation

Visual Dominance

It is naive to assume that a certain pattern of physical stimuli always elicits a particular veridical or illusory perceptual response. Certainly, when a pilot has a wide, clear view of the horizon, ambient vision adequately supplies virtually all orientation information, and potentially misleading linear or angular acceleratory motion cues do not result in SD (unless, of course, they are so violent as to cause vestibulo-ocular disorganization). When a pilot's vision is compromised by darkness or bad weather conditions, the same acceleratory motion cues can cause the development of SD; however, the pilot usually avoids it by referring to the aircraft instruments for orientation information. If the pilot is unskilled at interpreting the instruments, if the instruments fail or, as frequently happens, if the pilot neglects to look at the instruments, those misleading motion cues inevitably cause disorientation.

Visual dominance is the phenomenon in which one incorporates visual orientation information into his or her percept of spatial orientation to the exclusion of vestibular and nonvestibular proprioceptive, tactile, and other sensory cues. Visual dominance falls into two categories: the congenital type, in which ambient vision provides dominant orientation cues through natural neural connections and functions, and the acquired type, in which orientation cues are gleaned through focal vision and are integrated as a result of training and experience into an orientational percept. The functioning of the proficient instrument pilot illustrates acquired visual dominance; the aviator learns to decode with foveal vision the information on the attitude indicator and other flight instruments and to reconstruct that information into a concept of what the aircraft is doing and where it is going. This concept is referred to when controlling the aircraft. This complex skill must be developed through training and maintained through practice.

Vestibular Suppression

The term *vestibular suppression* is often used to denote the active process of visually overriding undesirable vestibular sensations or reflexes of vestibular origin. This is achieved through the practice of visual dominance. An example of this strategy is seen in well-trained figure skaters who, with much practice, learn to abolish the postrotatory dizziness, nystagmus, and postural instability that normally result from the high angular decelerations associated with suddenly stopping rapid spins on the ice. But even these individuals, when deprived of vision by eye closure or darkness, experience the dizziness, nystagmus, and falling that are the expected results from the acceleratory stimuli. In flight, the ability to suppress unwanted vestibular sensations and reflexes is developed with repeated exposure to the linear and angular accelerations of flight. As in the case of figure skaters, however, the pilot's ability to prevent vestibular sensations and reflexes is compromised when deprived of visual orientation cues by darkness, weather, and inadequate flight instrument displays.

Opportunism

Opportunism refers to the propensity of orientation-information processing systems to fill an orientation-information void swiftly and surely with natural orientation information. A pilot flying in instrument weather needs to look away from the artificial horizon for only a few seconds for erroneous ambient or visual or vestibular information to break through the pilot's defenses and become incorporated into an orientational percept. In fact, conflicts between focal visual and ambient visual or vestibular sources of orientation information often tend to resolve themselves very quickly in favor of the vestibular sensation, without providing the pilot an opportunity to evaluate the information.

It is logical that any orientation information reaching the vestibular nuclei, whether vestibular; other proprioceptive; or ambient visual, should have an advantage in competing with focal visual cues for expression as the pilot's sole orientational percept. This advantage is due to vestibular nuclei being primary terminals in the pathways for reflex orientational responses and initial level of integration for any eventual conscious perception of spatial orientation. In other words, although acquired visual dominance can be maintained by diligent attention to synthetic orientation cues, it is challenged by the processing of natural orientation cues through primitive neural channels, which are very potent and ever present.

The lack of adequate orientation cues and conflicts between competing sensory modalities are only a part of the disorientation mishap story. The reason why so many disoriented pilots, even those who know they are disoriented, are unable to recover their aircraft has mystified aircraft accident investigators for decades. There are two possible explanations for this phenomenon. The first suggests that the psychological stress of disorientation results in a disintegration of higher-order learned behavior, including flying skills. The second describes a complex psychomotor effect of disorientation that causes the pilot to feel the aircraft itself is misbehaving.

Disintegration of Flying Skill

The disintegration of flying skill perhaps begins with the pilot's realization that spatial orientation and control over the motion of the aircraft have been compromised. Under such circumstances, the pilot pays more heed to whatever orientation information is naturally available, monitoring it more and more vigorously. Whether the brainstem reticular-activating system or the vestibular efferent system or both are responsible for the resulting heightened arousal and enhanced vestibular information flow can only be surmised. The net effect, however, is that more erroneous vestibular information is processed and incorporated into the pilot's orientational percept. A positive-feedback situation is therefore encountered, and the vicious circle can now be broken only with a precisely directed and very determined effort by the pilot. Unfortunately, complex cognitive and motor skills tend to be degraded under the conditions of psychologic stress that occur during Type II or Type III

SD. First, there is a coning of attention. Pilots who have survived severe disorientation have reported that they concentrated on one particular flight instrument instead of scanning and interpreting the whole group in the usual manner. Pilots have also reported that they were unaware of radio transmissions to them while they were trying to recover from disorientation. Second, there is the tendency to revert to more primitive behavior, even reflex action, under conditions of severe psychologic stress. The highly developed, relatively newly acquired skill of instrument flying can give way to primal protective responses during disorientation stress, making appropriate recovery action unlikely. Third, it is often suggested that disoriented pilots become totally immobilized, frozen to the aircraft controls by fear or panic as the disintegration process reaches its final state.

Giant Hand

The giant hand phenomenon described by Malcolm and Money (60) explains why many pilots have been rendered hopelessly confused and ineffectual by SD, although they knew that they were disoriented and should have been able to avoid losing control of the aircraft. The pilot who has this effect of disorientation perceives falsely that the aircraft does not respond properly to his or her control inputs because every time the pilot tries to bring the aircraft to the desired attitude, it seems actively to resist his or her effort and return to another, more stable attitude. A pilot experiencing disorientation about the roll axis (e.g., the leans or graveyard spiral) may feel a force, like a giant hand, pushing one wing down and holding it there (Figure 6-37), whereas the pilot with pitch-axis disorientation (e.g., the classic somatogravic illusion) may feel the airplane subjected to a similar force holding the nose down. The giant hand phenomenon is not rare; one report states that 15% of pilots responding to a questionnaire on SD had experienced the giant hand (61). Pilots who are unaware of the existence of this phenomenon and experience it for the first time can be very surprised and confused by it and may not be able to discern the exact nature of the problem. A pilot's radio transmission indicating the aircraft controls are malfunctioning should not, therefore, be taken as conclusive evidence that a control malfunction caused a mishap: SD could have been the real cause.

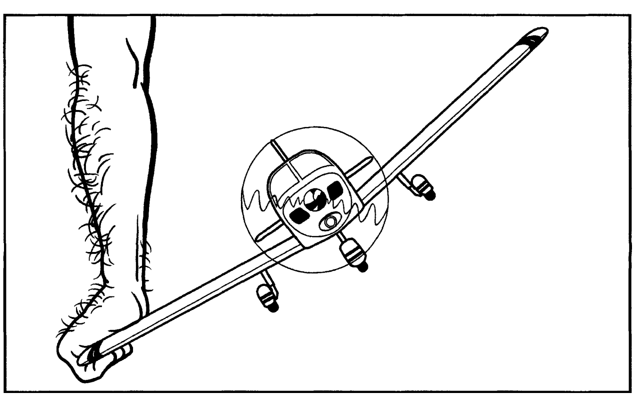


FIGURE 6-37 The giant hand phenomenon. This pilot, who is disoriented with respect to roll attitude (bank angle), feels the aircraft is resisting his conscious attempt to bring it to the desired attitude according to the flight instruments, as though a giant hand is holding it in the attitude compatible with his erroneous natural sense of roll attitude.

What mechanism could possibly explain the giant hand? To understand this phenomenon, we must first recognize that an individual's perception of orientation results not only in the conscious awareness of the position and motion but also in a preconscious percept needed for the proper performance of voluntary motor activity and reflex actions. A conscious orientational percept can be considered rational in that one can subject it to intellectual scrutiny, weigh the evidence for its veracity, conclude that it is inaccurate, and to some extent modify the percept to fit facts obtained from other primary orientation senses. In contrast, a preconscious orientational percept must be considered irrational, in that it consists of an integration of data relayed to the brainstem and cerebellum by the primary orientation senses and is not amenable to modification by reason. What happens when a pilot knows he or she has become disorientated and tries to control the aircraft by reference to a conscious rational percept of orientation that is in conflict with a preconscious, irrational one? The data comprising one's preconscious orientational percept are available for the performance of orientational reflexes (e.g., postural reflexes) and a large part of skilled voluntary motor activity (e.g., walking, bicycling, and flying). The actual outcome of these types of actions will often deviate from the rationally intended outcome whenever the orientational data on which the pilot depends are different from the rationally perceived orientation. The disoriented pilot who consciously commands a roll to recover aircraft control may experience a great deal of difficulty in executing the command because the informational substrate in reference to which his or her body functions indicates that such a move is counterproductive or even dangerous. Or the pilot may discover that the roll, once accomplished, must be repeated because preconsciously influenced arm motions automatically keep returning the aircraft to its original flight attitude despite his or her conscious efforts and actions to regain control. Therefore, the preconscious orientational percept influences Sherrington's "final common pathway" for both reflex and voluntary motor activity, and the manifestation of this influence on the act of flying during an episode of SD is the giant hand phenomenon. To prevail in this conflict between will and skill, the pilot must decouple his or her voluntary acts from automatic flying behavior. It has been suggested that using the thumb and forefinger to move the control stick, rather than using the whole hand, can effect the necessary decoupling and thereby facilitate recovery from the giant hand.

Conditions Conducive to Disorientation

Knowledge of the physiologic basis of the various illusions of flight allows us to infer many of the specific environmental factors conducive to SD. Certain visual phenomena produce characteristic visual illusions such as false horizons and vection. Prolonged turning at a constant rate, as in a holding pattern or procedure turn, can precipitate somatogyral illusions or the leans. Relatively sustained linear accelerations, such as occur on takeoff, can produce somatogravic illusions, and head movements during high-G turns can elicit G-excess illusions.

But what are the regimens of flight and activities of the pilot that seem most likely to allow these potential illusions to manifest themselves? Certainly, instrument weather and night flying are primary factors. The practice of switching back and forth between the instrument flying mode and the visual, or contact, flying mode is especially likely to produce disorientation. A pilot is far less likely to become disoriented if he or she uses the instruments as soon as out-of-cockpit vision is compromised and stays on the instruments until continuous contact flying is assured. In fact, any event or practice requiring the pilot to break his or her instrument cross-check is conducive to disorientation. In this regard, avionics control switches and displays in some aircraft are located so that the pilot must interrupt the instrument cross-check for more than just a few seconds to interact with them and are therefore known as *vertigo traps*. Some of these vertigo traps require substantial movements of the pilot's head during the instrument or procedure cross-check, thereby providing both a reason and an opportunity for SD to strike.

Formation flying in adverse weather conditions is probably the most likely situation of all to produce disorientation; indeed, some experienced pilots get disoriented every time they fly wing or trail in weather. The fact that formation pilots have little if any opportunity to scan the flight instruments while flying on the lead aircraft in weather means that they are essentially isolated from any source of accurate orientation information, and misleading vestibular and ambient cues arrive unchallenged into the orientational sensorium.

The important factors to the pilot in preventing SD are confidence, competency, and currency in instrument flying. It is virtually assured that a non–instrument-rated pilot who penetrates instrument weather will develop SD within a matter of seconds, just as a competent instrument-rated pilot will develop it if he or she flies in weather without functioning flight instruments. Regarding instrument flying skill, one must "use it or lose it," as they say. For that reason, it is inadvisable (and perhaps illegal) for a pilot to be in command of an aircraft in instrument weather if he or she has not had a certain amount of recent instrument flying experience.

Even highly capable instrument pilots are susceptible to SD, if their attention is diverted away from the flight instruments. This can happen when other duties such as navigation, communication, operating weapons, responding to malfunctions, and managing in-flight emergencies place excessive demands on the pilot's attention. The aviator becomes "task saturated." In fact, virtually all aircraft mishaps involving Type I SD occur as a result of the pilot's failure to prioritize multiple tasks properly. A rule of thumb taught from day 1 of flight school is to fly the airplane first and then do the other things as time allows. This is always good advice for pilots, especially for those faced with a high mental workload because not to prioritize in this manner can result in disorientation and disaster.

Finally, conditions affecting the physical or mental health must be considered capable of rendering the pilot more susceptible to SD. The unhealthy effect of alcohol ingestion on neural-information processing is one obvious example. However, the less well-known ability of alcohol to produce vestibular nystagmus (positional alcohol nystagmus), for many hours after its more overt effects have disappeared, is probably of equal significance. Use of other drugs, such as barbiturates, amphetamines, nonprescription drugs (such as antihistamines) and especially illegal "recreational" drugs (see Chapter 9), certainly could contribute to the development of disorientation and precipitate aircraft mishaps. Likewise, physical and mental fatigue, as well as acute or chronic emotional stress, can rob the pilot of the ability to concentrate on the instrument cross-check and can, therefore, have deleterious effects on his or her resistance to SD.

Prevention of Disorientation Mishaps

SD can be attacked in several ways. Theoretically, each link in the physiologic chain of events leading to a disorientation-related mishap can be mitigated by a specific countermeasure (Figure 6-38). Many times, SD can be prevented by modifying flying procedures to avoid those visual or vestibular motion and position stimuli that tend to create illusions in flight. Improving the capacity of flight instruments to translate aircraft position and motion information into readily assimilated orientation cues will help the pilot to avoid disorientation. Pilots become proficient in instrument flying through repeated exposures to the environment of instrument flight due to the development of perceptual processes that result in accurate orientational percepts rather than orientational illusions. If a pilot experiences an orientational illusion but has relegated primary control of flight parameters to autopilot rather than directly controlling the aircraft, it is essentially irrelevant because the pilot has spatial unorientation rather than disorientation.

Use of an autopilot can help prevent disorientation and also help the pilot recover from it when the disoriented pilot engages autopilot and ride as a passenger until safely able to reclaim primary control of the aircraft. Indeed, some fighter aircraft have a special "panic switch," which the disoriented pilot can activate to bring the aircraft back to a wings-level attitude.

If a pilot who has developed SD has the capability to recognize that he or she is disoriented, that pilot is well along the road to recovery. Recognizing disorientation is not necessarily easy, however. First, the pilot must be aware that he or she is having a problem holding altitude or heading; the pilot cannot do this while concentrating on something other than the flight instruments, such as the radar scope. Only through proper flight training can the appreciation of the need for appropriate task prioritization and the discipline of continuously performing the instrument cross-check be instilled. Second, the pilot must recognize that

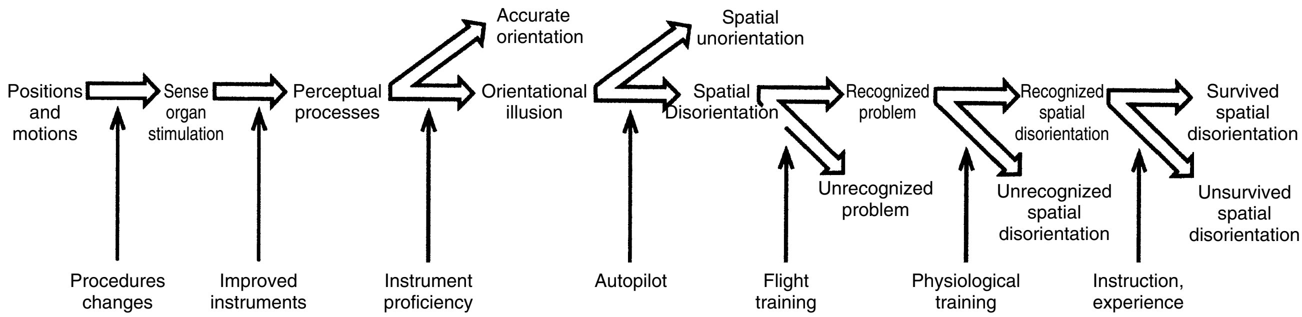


FIGURE 6-38 The chain of events leading to a spatial disorientation mishap, and where the chain can be attacked and broken. From the left: Flight procedures can be altered to generate less confusing sensory inputs. Improved instrument presentations can aid in the assimilation of orientation cues. Proficiency in instrument flying helps to assure accurate orientational percepts. In the event the pilot has an orientational illusion, having the aircraft under autopilot control, avoids disorientation by substituting unorientation. Flight training helps the pilot prioritize his various tasks properly so he can recognize quickly that the aircraft is not flying the desired flight path. Once the pilot knows that a problem exists, the physiological training helps him or her realize that the problem is spatial disorientation. With appropriate instruction and/or firsthand experience, the pilot with recognized spatial disorientation can apply the correct control forces to recover the aircraft and survive the disorientation incident.

the difficulty in controlling the aircraft is a result of SD. This ability is promoted through physiological training. Finally, a pilot's ability to cope with the effects of disorientation on control inputs to the aircraft comes through effective flight instruction, proper physiological training, and experience in controlling a vehicle in an environment of conflicting orientation cues. The pilot's simply being aware that he or she is disoriented, by no means ensures survival.

Education and Training

Physiological training and the knowledge of how to do a good instrument cross-check is the main weapon against SD at the disposal of the pilot, flight surgeon/aviation medical examiner, and aerospace physiologist. The training ideally should consist of didactic material, demonstrations, and interactive training. There is no paucity of didactic material on the subject of disorientation: numerous films, video computer programs, handbooks, and chapters in books and manuals have been prepared for the purpose of informing the pilot about the mechanisms and hazards of SD. Although the efforts to generate information on SD are commendable, there is a tendency for such didactic material to dwell too much on the mechanisms and effects of disorientation without giving much practical advice on how to deal with it.

We now emphasize to pilots a two-stage approach for preventing disorientation mishaps. First, minimize the likelihood of SD by monitoring frequently and systematically the critical flight parameters (bank, pitch, vertical velocity, and altitude) displayed by the flight instruments or a valid natural reference; conversely, expect to become disoriented if attention to these flight parameters is allowed to lapse as a result of misprioritizing the tasks at hand. Second, when disorientation does occur, recognize it as such and act. In the past, the standard advice was to believe the instruments. Now this message by itself is inadequate, because the pilot in a stressful, time-critical situation needs to know what to do to extricate himself or herself from the predicament, not merely how to analyze it. If a pilot is told to make the instruments read right, regardless of your sensation, he or she has simple, definite instructions on how to bring the aircraft under control when disorientation strikes. We strongly advise that every presentation to pilots on the subject of SD emphasize (a) the need to avoid disorientation by making frequent instrument cross-checks, and (b) the need to recover from disorientation by making the instruments read right.

The traditional demonstration accompanying lectures to the pilots on SD is a ride on a Barany chair or Vista Vertigon, or some other smoothly rotating device, a tradition going back to the Ocker Box of the 1920s (62).

Sitting in the device with eyes closed, pilot trainees are accelerated to a constant angular velocity and asked to signal their perceived direction of turning. After a number of seconds (usually from 10 to 20) at constant angular velocity, the trainee loses the sensation of rotation and signals this fact to the observers. The instructor then suddenly stops the rotation, whereupon the trainee immediately indicates that he or she has a feeling of turning in the direction opposite to the original direction of rotation. Pilot trainees are usually asked to open their eyes during this part of the demonstration and are amazed to see that they are actually not turning, despite the strong vestibular sensation of rotation. It is best to have other pilot trainees witness this effect. After the described demonstration of somatogyral illusions, the trainee is again rotated at a constant velocity with eyes closed, this time with head down (facing the floor). When the pilot trainee indicates the sensation of turning has ceased, the trainee is asked to raise the head abruptly so as to face the wall. The Coriolis illusion resulting from this maneuver is one of a very definite roll to one side; the startled trainee may exhibit a protective postural reflex and may open the eyes to help visually orient during this falsely perceived upset. The message delivered with these demonstrations is not that such illusions will be experienced in flight in the same manner, but that the vestibular sense can be unreliable and that only flight instruments provide accurate orientation information.

Over the years, at least a dozen different training devices have been developed to augment or supplant the Barany chair for demonstrating various vestibular and visual illusions and the effects of disorientation in flight. These devices fall into two basic categories: orientational illusion demonstrators and SD demonstrators. The majority are illusion demonstrators, in which the trainee rides passively and experiences one or more of the following: somatogyral, oculogyral, somatogravic, oculogravic, Coriolis, G excess, vection, false horizon, and autokinetic illusions. In an illusion demonstrator, the trainee is typically asked to record or remember the magnitude and direction of the orientational illusion and is then told or otherwise allowed to experience true orientation. A few devices actually put the trainee in the motion control loop and allow him or her to experience the difficulty in controlling the attitude and motion of the device while being subjected to various vestibular and visual illusions. These devices are labeled SD trainers although they are really SD countermeasure trainers. They are not demonstrators only. However, it has yet to be shown that they actually produce effective training by changing behavior of the pilot. Figure 6-39 shows two such SD demonstrators presently in use, but there are many others of increasing sophistication.

Although the maximal use of ground-based SD training devices in the physiological training of pilots is to be encouraged, it is important to recognize the great potential for misuse of such devices by personnel not thoroughly trained in their theory and function. Several devices have aircraft-instrument tracking tasks for the trainee to perform while they are experiencing orientational illusions, but not actually controlling the motion of the trainer. The temptation is very strong for unsophisticated operating personnel to tell the trainees that they are "fighting disorientation" if they perform well on the tracking task while being subjected to the illusion-generating motions. Because the trainees' real orientation is irrelevant to the tracking task, any orientational illusion is also irrelevant and they experience no conflict between visual and vestibular information in acquiring cues on which to base the control responses. This situation, of course, does not capture the essence of disorientation in flight, and the trainees who are led to believe they are fighting disorientation in such a ground-based demonstration may develop a false sense of security about their ability to combat disorientation in flight. The increasing use of SD demonstrators in which the subject must control the actual motion of the trainer by referring to true-reading instruments while under the influence of orientational illusions will reduce the potential for misuse and improve the effectiveness of presentations to pilots on the subject of SD.

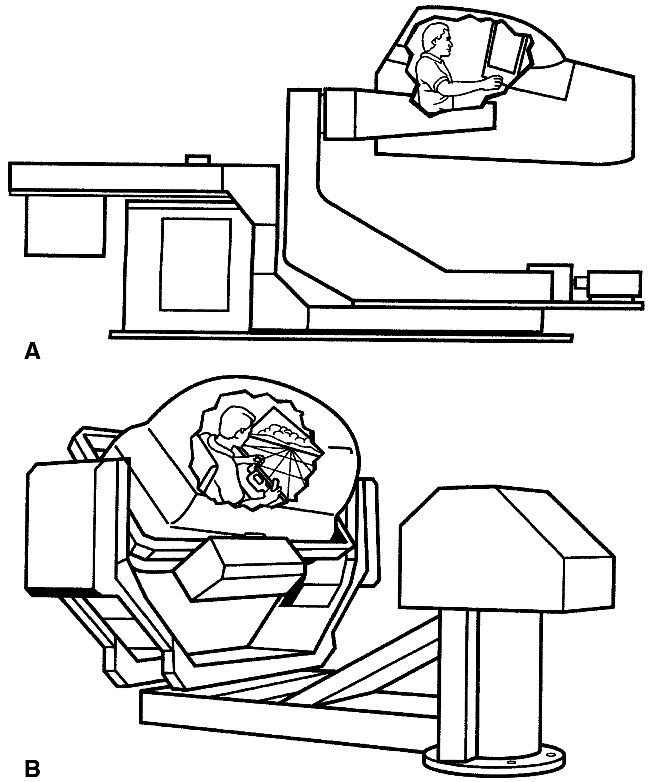


FIGURE 6-39 Two classic spatial disorientation demonstrators for physiologic training: the Model 2400 Vertifuge (**A**) and the Gyrolab 3000 (**B**). Both devices use somatogyral, somatogravic, and other vestibular illusions, as well as focal and ambient visual illusions, to create disorientation in the trainee, who "flies" the cockpit by reference to flight instruments.

Flight training provides a good opportunity to instruct pilots about the hazards of SD. In-flight demonstrations of vestibular illusions are included in most formalized pilot training curricula, although the efficacy of such demonstrations is highly dependent on the motivation and skill of the individual flight instructor. Somatogyral and somatogravic illusions and illusions of roll attitude can be induced in a student pilot by a flight instructor who understands how the vestibular system works and/or knows from experience which maneuvers consistently produce illusions. The vestibular illusion demonstrations should not be confused with the unusual-attitude-recovery demonstrations in the typical pilot training syllabus. The objective of the former is for the student to experience orientational illusions and recognize them as such, whereas the objective of the latter is for the student to learn to regain control of an aircraft in a safe and expeditious manner. In both types of demonstration, however, control of the aircraft should be handed over to the student pilot with the instruction to make the instruments read right.

The importance of continuance maintenance of flying proficiency as a part of flight training cannot be overemphasized in reducing the likelihood of having a disorientation mishap. Whether flying instruments in formation or in acrobatic maneuvering, familiarity with the environment (based on recent exposure to it) and proficiency at the flying task (based on recent practice at it) result not only in a greater ability to avoid or dispel orientational illusions but also in a greater ability to cope with disorientation when it does occur.

In-flight Procedures

If a particular in-flight procedure frequently results in SD, it stands to reason that modifying or eliminating that procedure should help to reduce aircraft mishaps due to disorientation. Night formation takeoffs and rejoins are examples of in-flight procedures that are very frequently associated with SD.

Another area of concern is the "lost wingman" procedure, which is used when a pilot has lost sight of the aircraft on which he or she has been flying wing. Usually the loss of visual contact is due to poor visibility and occurs after a period of vacillation between formation flying and instrument flying; this, of course, invites disorientation. The lost wingman procedure must, therefore, be made as uncomplicated as possible while still allowing safe separation from the other elements of the flight. Maintaining a specified altitude and heading away from the flight until further notice is an ideal lost wingman procedure in that it avoids frequent or prolonged disorientation-inducing turns and minimizes cognitive workload. Often, a pilot flying wing in bad weather does not lose sight of the lead aircraft but has so much disorientation stress that it makes the option of going lost wingman seem safer than continuing in the formation. A common practice in this situation is for the wingman to take the lead position in the formation, at least until the disorientation disappears. This avoids the necessity of having the disoriented pilot make a turn away from the flight to go lost wingman, a turn that could be especially difficult and dangerous because of the disorientation. One should question the wisdom of having a disoriented pilot leading a flight, however, and some experts in the field of SD are adamantly opposed to this practice, with good reason.

Verbal communication can help keep a pilot from becoming disoriented during formation flying in weather, when workload is high and the pilot's visual access to the flight instruments is by necessity infrequent. The leader of the flight should report periodically to the wingman what the flight is doing; that is, the lead should announce the pitch and bank attitude, altitude, vertical velocity, heading, and airspeed as necessary to allow the wingman to construct a mental image of the spatial orientation. If the wingman has already become disoriented, the lead pilot still needs to tell the wingman the correct orientation information, and also needs to provide some potentially life-saving advice about what to do. Unfortunately, no clear-cut procedure exists for ensuring appropriate communications, but most instructor pilots will instinctively tell their wingman (when disoriented) to get on the round dials, which means to get on the instruments.

Should disoriented pilots be hounded mercilessly with verbal orders to get on the instruments or should they be left relatively undistracted to solve their orientation problem? The extremes of harassment and neglect are definitely not appropriate; a few forceful, specific, action-oriented commands probably represent the best approach. "Level the artificial horizon!" and "Roll right 90 degrees!" are examples of such commands. One must remember that the pilot who has SD may be either so busy or so functionally compromised that complex instructions may fall on deaf ears. Simple, emphatic directions may be the only means of penetrating the disoriented pilot's consciousness. Recommendations regarding in-flight procedures are discussed before flight when SD is a potential concern.

Cockpit Layout and Flight Instruments

One of the most notorious vertigo traps is the transceiver frequency selector or transponder code selector, which is located in an obscure part of the cockpit. Manipulating this selector requires the pilot not only to look away from the flight instruments, interrupting an instrument scan, but also to tilt the head to view the readout which potentially subjects the pilot to G-excess and Coriolis illusions. Aircraft designers are now aware that easy accessibility and viewing of such frequently used devices minimizes the potential for SD; accordingly, most modern aircraft have communications frequency and transponder code selectors and readouts located in front of the pilot near the flight instruments.

The location of the flight instruments themselves is also very important. They should be clustered directly in front of the pilot and the attitude indicator, the primary provider of orientation cueing and the primary instrument by which the aircraft is controlled, should be in the center of the cluster (Figure 6-40). When this principle is not respected, the potential for SD is increased. One modern fighter aircraft, for example, was designed to have the pilot sitting high in the cockpit to enhance the field-of-view during air-to-air combat in conditions of good visibility. This design relegates the attitude indicator to a position more or less between the pilot's knees. As a result, at night and during instrument

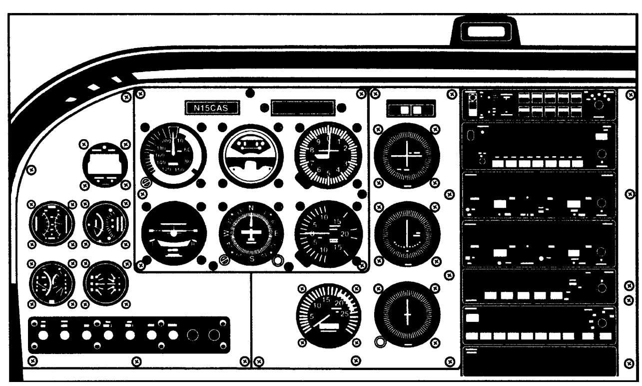


FIGURE 6-40 A well-designed instrument panel, with the attitude indicator located directly in front of the pilot and the other flight instruments clustered around it. Radios and other equipment requiring frequent manipulation and viewing are placed close to the flight instruments to minimize interruption of the pilot's instrument scan and to reduce the need to make head movements that could precipitate spatial disorientation. (Photo courtesy of Gen-Aero Inc. of San Antonio, Texas.)

weather, the pilot is subjected to potentially disorienting peripheral visual motion and position cueing by virtue of being surrounded by a vast expanse of canopy, while he or she tries to glean with central vision the correct orientation information from a relatively small, distant attitude indicator. The net effect is an unusually difficult orientation problem for the pilot and a greater risk of developing SD in this aircraft than in others with a more advantageously located attitude indicator.

The verisimilitude of the flight instruments is a major factor in their ability to convey readily assimilatable orientation information. The old "needle, ball, and airspeed" indicators required much interpretation for the pilot to perceive his or her spatial orientation through them. Nevertheless, this combination sufficed for nearly a generation of pilots. When the attitude indicator (also known as the *gyro horizon, artificial horizon*, or *attitude gyro*) was introduced, it greatly reduced the amount of work required to spatially orient during instrument flying because the pilot could readily imagine the artificial horizon line to be the real horizon. In addition to becoming more reliable and more versatile over the years, it became even easier to interpret because the face was divided into a gray or blue "sky" half and a black or brown "ground" half, with some models even having lines of perspective converging to a vanishing point in the lower half. Such a high degree of similarity to the real world has made the attitude indicator the mainstay of instrument flying now.

The most noticeable improvement to flight instrumentation is the head-up display or HUD. The HUD projects numeric and other symbolic information to the pilot from a combining glass near the windscreen, so that he or she can be looking forward out of the cockpit and simultaneously monitoring flight and weapons data. When the pilot selects the appropriate display mode, the pitch and roll attitude of the aircraft are observed on the "pitch ladder" (Figure 6-41) and heading, altitude, airspeed, and other parameters are numerically displayed elsewhere on the HUD. Its up-front location and its close arrangement of most of the required aircraft control and performance data make the HUD a possible improvement over the conventional cluster of instruments with regard to minimizing the likelihood of SD. Acceptance and use of the HUD for flying in instrument weather has received remarkable widespread acceptance. HUDs are now found in every fighter aircraft and almost in all new military cargo aircraft. HUDs have been installed in commercial airliners with Alaska Airlines leading the way in 2002 (Figure 6-42).

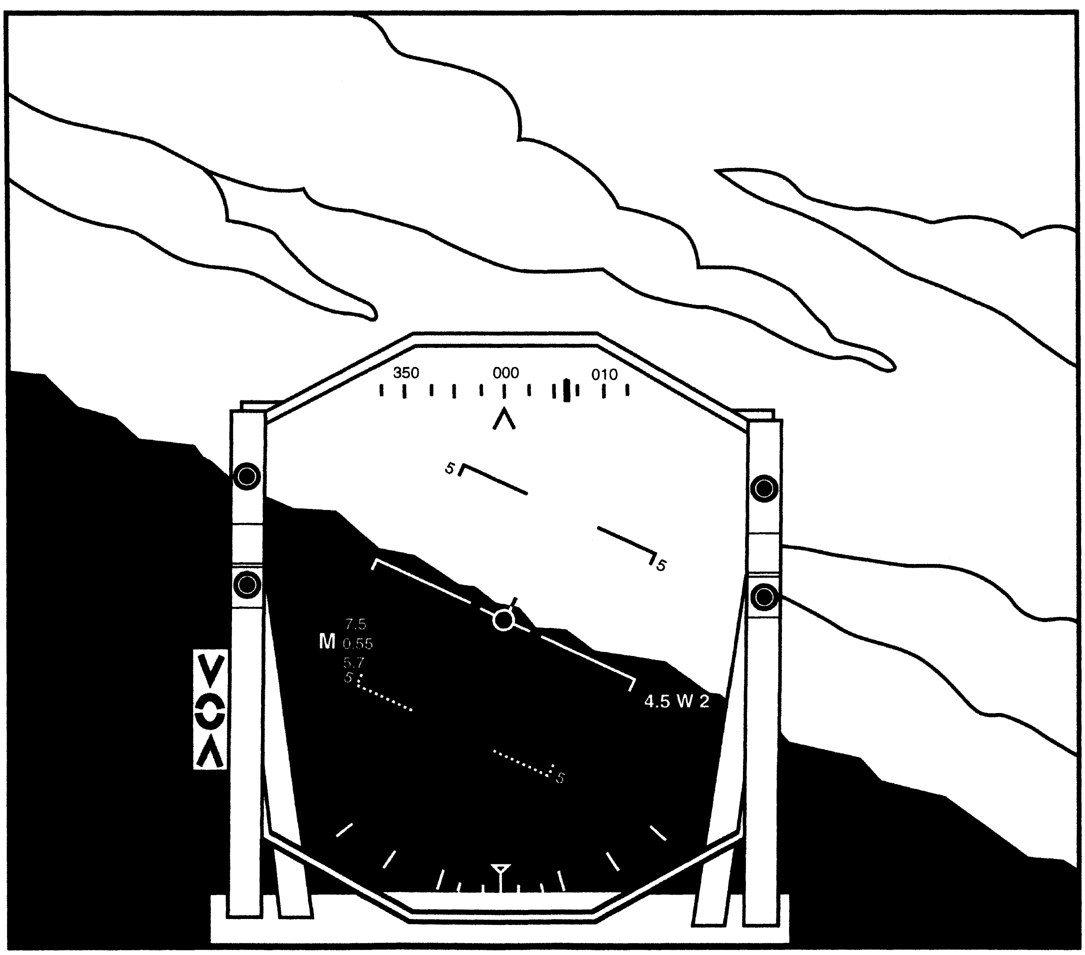


FIGURE 6-41 A typical head-up display (HUD). The pitch ladder in the center of the display provides pitch and roll attitude information.

FIGURE 6-42 Head-up display (HUD) used by Alaska Airlines.

The next stage is the helmet/head mounted display (HMD), which no longer limits the pilot to the area directly in front of the aircraft. Instead, as the pilot turns the head, the display moves with him or her. This is understandable, because in some ways the HUD is inferior to the conventional flight instruments in being able to provide spatial orientation information that can readily be assimilated. The HUD presents a relatively narrow view of the outside world; a "vernier" view with high resolution whereas the conventional attitude indicator gives an expansive, "global" view of the spatial environment. Another reason is that the relative instability of the HUD pitch ladder and the frequency with which the zero-pitch line (horizon) disappears from view make the HUD difficult to use during moderately active maneuvering, as would be necessary during an unusual attitude recovery attempt. A third reason may be that the horizon on the conventional attitude instrument looks more like the natural horizon than does the zero-pitch line on the HUD pitch ladder. Nevertheless, the HUD is the sole source of primary (aircraft control and performance) flight information in many of the present day fighter aircraft, for example, F/A-18 Hornet, F-16 Falcon, and the new F-22 Raptor.

A HUD is even available in certain automobiles. Attempts to eliminate the potpourri of HUD symbologies and arrive at a maximally efficient, standardized display are also being made.

As good as they are, both the attitude indicator and the HUD leave much to be desired as flight instruments for assuring spatial orientation. Both have the basic design deficiency of presenting visual spatial-orientation information to the wrong sensory system, the focal visual system. Two untoward effects result. First, the pilot's focal vision not only must serve to discriminate numeric data from a number of instruments but also must take on the task of spatially orienting the pilot. Therefore, the pilot has to employ the focal vision system in a somewhat inefficient manner during instrument flight, with most of the time spent viewing the attitude indicator or pitch ladder, while ambient vision remains unutilized (or worse, is being bombarded with misleading orientational stimuli). Second, the fact that focal vision is not naturally equipped to provide primary spatial orientation cues causes difficulty for pilots in interpreting the artificial horizon directly.

There is a tendency, especially among novice pilots, to interpret the displayed deviations in roll and pitch backward and to make initial roll and pitch corrections in the wrong direction. Several approaches tried to improve the efficiency of the pilot's acquisition of orientation information from the attitude indicator and associated flight instruments. One approach has been to make the artificial horizon stationary but to roll and pitch the small aircraft on the instrument display to indicate the motion of the real aircraft (the so-called outside-in presentation, as opposed to the inside-out presentation of conventional attitude displays). Theoretically, this configuration relieves the pilot of having to orient spatially before trying to fly the aircraft; rather, the pilot merely flies the small aircraft on the attitude instrument and the real aircraft follows. Another approach involves letting the artificial horizon provide pitch information, but having the small aircraft on the attitude instrument provide roll information (62).

Neither of these approaches frees foveal vision from the unnatural task of processing spatial orientation information.

Another concept, the peripheral vision display (PVD), also known as the *Malcolm horizon*, attempts to give pitch and roll cues to the pilot through his or her peripheral vision, thereby sparing foveal vision for tasks requiring a high degree of visual discrimination. The PVD projects a long, thin line of light representing the true horizon across the instrument panel; this line of light moves directly in accordance with the relative movement of the true horizon (Figure 6-43). The PVD has been incorporated into at least one military

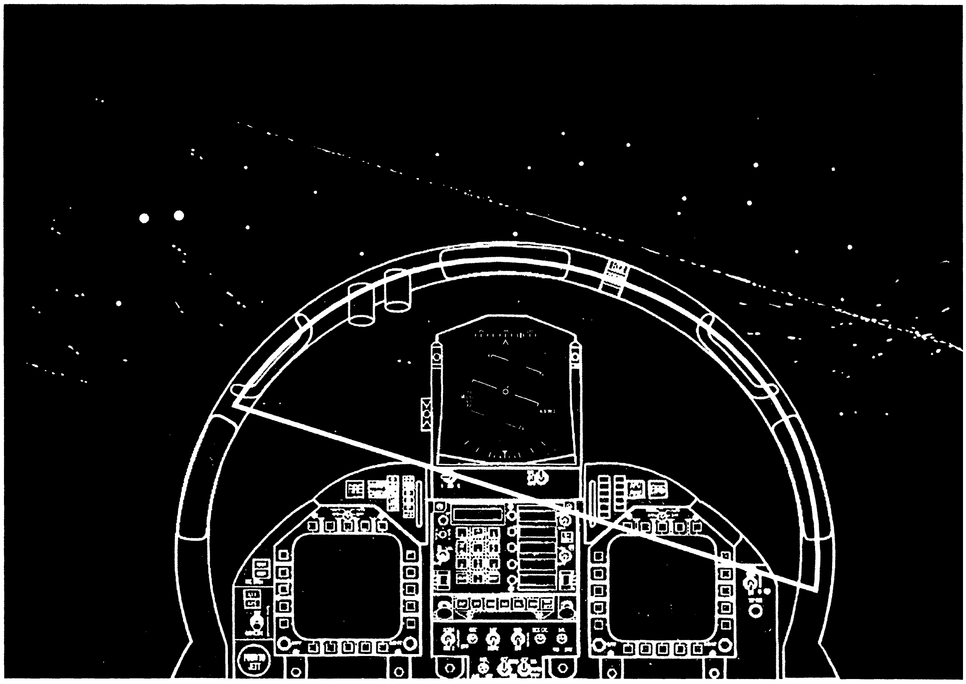


FIGURE 6-43 The peripheral vision display (PVD) or Malcolm horizon. An artificial horizon projected across the instrument panel moves in accordance with the real horizon, and the pilot observes the projected horizon and its movement with ambient vision.

aircraft, but its limited pitch display range and certain other characteristics have prevented an enthusiastic acceptance of this display concept.

The eventual solution to the SD problems lies, we believe, in HMD technology. The revolution in computer image generation and advances in optical and acoustic techniques will ultimately allow the display of a synthesized representation of the natural spatial environment over the full visual field at optical infinity and in three dimensions of auditory space (Figure 6-44). Current displays are now the size of spectacles, weighing only a few grams and provide the pilot with situational orientation regardless of the attitude of the head relative to the aircraft. The next step is to reach the point where an electronically enhanced visual and auditory spatial environment is displayed superimposed on the real world, so that the pilot can spatially orient in a completely natural manner, using a synthetic device. Other input including auditory and tactile displays can augment such a system.

Other Sensory Phenomena

Flicker vertigo, fascination, and target hypnosis are traditionally described in conjunction with SD, although, strictly speaking these entities involve alterations of attention rather than aberrations of perception. Neither is the break-off phenomenon related directly to SD, but the unusual sensory manifestations of these conditions make a discussion of it here seem appropriate.

Flicker Vertigo

As most people are aware from personal experience, viewing a flickering light or scene can be distracting, annoying, or both. In aviation, flicker is sometimes created by helicopter rotors or idling airplane propellers interrupting direct sunlight or, less frequently, by such things as several anticollision lights flashing asynchronously. Pilots report that such conditions are indeed a source of irritation and distraction, but there is little evidence that flicker induces either SD or clinical vertigo in normal aircrew. In fact, one authority insists there is no such thing as flicker vertigo and that the original reference was merely speculation (63). Certainly, helicopter rotors or rotating beacons on aircraft can produce angular vection illusions because they create revolving shadows or revolving areas of illumination; however, vection does not result from flicker. Symptoms of motion sickness also conceivably result from the sensory conflict associated with angular vection but, again, these symptoms would be produced by revolving lights and shadows and not by flicker.

Nevertheless, one should be aware that photic stimuli at frequencies in the 8- to 14-Hz range, that of the electroencephalographic alpha rhythm, can produce seizures in those rare individuals who are susceptible to flicker-induced epilepsy. Although the prevalence of this condition is very low (<1 in 20,000), and the number of pilots affected are very few, some helicopter crashes are thought to have been caused by pilots who have flicker-induced epilepsy.

Fascination

Coning of attention is something everyone experiences every day, but it is especially likely to occur when one is stressed by the learning of new skills or by the relearning of old

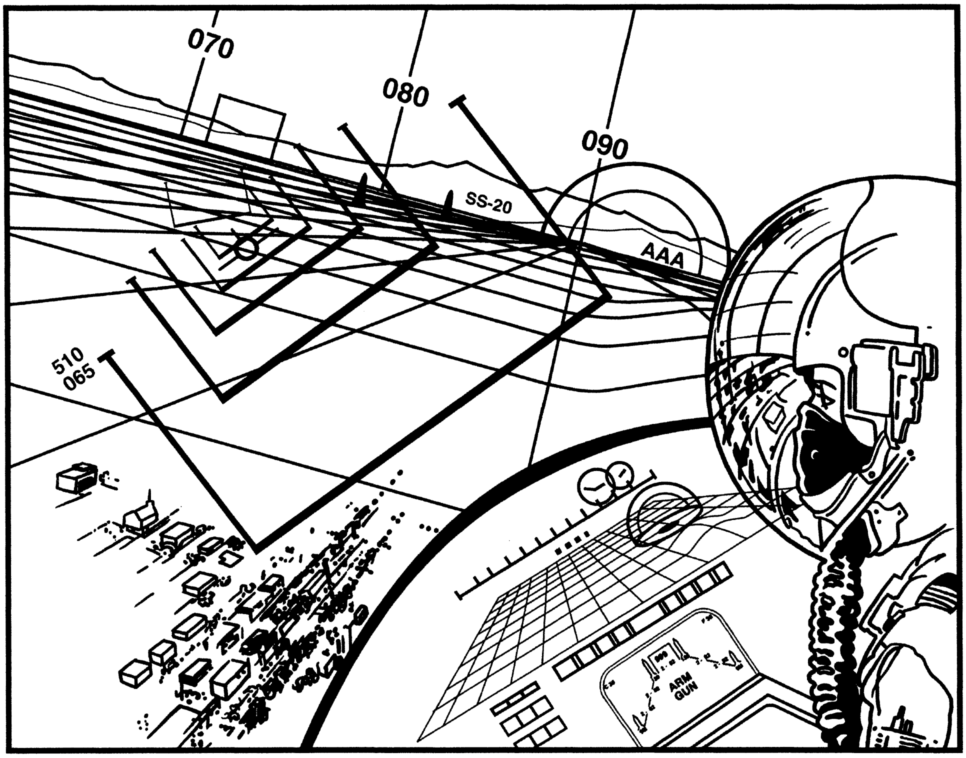


FIGURE 6-44 Artist's concept of an advanced helmet-mounted display. A computer-generated image of the plane of the Earth's surface and other critical flight information are displayed on the helmet visor at optical infinity, superimposed on the real world.

ones. Pilots are apt to concentrate on one particular novel or demanding aspect of the flying task to the relative exclusion of others. If this degree of concentration is sufficient enough to cause the pilot to disregard important information to which they should respond, it is termed *fascination*. An extreme example of fascination is when the pilot becomes so intent on delivering weapons to the target that he or she ignores the obvious cues of ground proximity and fly into the ground. Mishaps of this sort are said to result from target fixation or hypnosis; no actual hypnotic process is suspected or should be inferred. Other examples of fascination in aviation are (a) the monitoring of one flight instrument rather than cross-checking many of them during particularly stressful instrument flight, (b) paying so much attention to flying precise formation that other duties are neglected, and (c) the aviator's most ignominious act of negligence, landing an airplane with the landing gear up, despite the clearly perceived warning from the gear-up warning horn. These examples help us to appreciate the meaning of the original definition of fascination by Clark et al.: "a condition in which the pilot fails to respond adequately to a clearly defined stimulus situation in spite of the fact that all the necessary cues are present for a proper response and the correct procedure is well known to him" (64). From the definition and the examples given, it is clear that fascination can involve either a sensory deficiency or an inability to act, or perhaps both. It is also known that fascination, at least the type involving sensory deficiency, occurs not only under conditions of relatively high workload but can also occur when work load is greatly reduced and tedium prevails. Finally, the reader should understand that coning or channeling of attention, such as occurs with fascination, is not the same thing as tunneling of vision, which occurs with G stress. Even if all pertinent sensory cues could be made accessible to foveal vision, the attention lapses associated with fascination could still prevent those cues from being perceived or eliciting a response.

Break-off

In 1957, Clark and Graybiel (65) reported a condition that is perhaps best described by the title of their paper: "The break-off phenomenon-a feeling of separation from the Earth experienced by pilots at high altitude." They interviewed 137 U.S. Navy and Marine Corps jet pilots and found 35% had experienced feelings of being detached, isolated, or physically separated from the Earth when flying at high altitudes. The three conditions most frequently associated with the experience were (a) high altitude (approximately 5,000–15,000 with a median of 10,000 m or 15,000, 45,000, and 33,000 ft, respectively), (b) being alone in the aircraft, and (c) not being particularly busy with operating the aircraft. Most of the pilots interviewed found the break-off experience exhilarating, peaceful, or otherwise pleasant; more than a third, however, felt anxious, lonely, or insecure. No operational impact could be ascribed to the break-off phenomenon; specifically, it was not considered to have any significant effect on a pilot's ability to operate the aircraft. The authors nevertheless suggested that the break-off experience might have significant effects on a pilot's performance when coupled with preexisting anxiety or fear, and for that reason, the phenomenon should be described to pilots before they fly alone at high altitudes for the first time. Break-off may, on the other hand, have a profound, positive effect on the motivation to fly. Who could deny the importance of this experience to John Gillespie Magee Jr., who gave us "High Flight," the most memorable poem in aviation?

> "Oh, I have slipped the surly bonds of the Earth . . . Put out my hand, and touched the face of God."

SITUATIONAL AWARENESS

A corollary to spatial orientation is situational awareness. The pilot must also know the attitude and position of the aircraft with respect to the Earth. Loss of situational awareness may leave the pilot oriented in space, but not in geography. Failure to know if you are approaching or have safely flown past a mountain is critical in deciding when to begin descent. This is not the same thing as being lost. An agricultural spray pilot must know where the target field is as well as the local hazards, such as power lines and trees.

Modern aircraft with "glass cockpits" and advanced computerized navigation systems can leave a pilot complacent or intimidated by the systems. A common problem encountered by commercial airline pilots advancing to glass cockpit aircraft with these Flight Management Systems (FMS) is to have great difficulty understanding what the system is doing and exactly what the computer commands mean when they are given. As an example, a commercial airliner, B757, inbound to Cali, Columbia in 1995 was flying at night down a mountain valley. The pilots did not realize that they had already flown past a navigation checkpoint and when they tried to program the FMS using a shorthand code to take them directly to Cali. Instead, a checkpoint approximately 200 mi away at their 7:00 position was selected. The FMS obediently turned the aircraft toward the new checkpoint, and due to the very dark night and absence of outside visual clues, the pilots did not see that they were turning directly toward a mountain. Likewise the ground controller, who had no radar available, was not aware of the aircraft's actual location and was also situationally unaware. This was fatal to 159 of the 163 on board.

Loss of situational awareness can occur even on the ground. Runway incursions are a major problem facing the Federal Aviation Administration (FAA), particularly due to the fact that so many U.S. airports are uncontrolled. Runway incursions lead to the worst aircraft accident in history when two 747s collided on a Tenerife runway in the Canary Islands in 1977 due to poor visibility and poor communication leading to the loss of situational awareness by one of the pilots and the tower operator. Better runway markings and new electronic displays are part of the solution (66).

MOTION SICKNESS

Motion sickness is a perennial aeromedical problem. The important syndrome is discussed in this chapter to emphasize the critical importance of the spatial orientation senses in its pathogenesis. So closely entwined, in fact, are the mechanisms of spatial orientation and those of motion sickness that orientation is sometimes (and legitimately) used as the general term for the category of related conditions that are commonly referred to as *motion sickness*.

Definition, Description, and Significance of Motion Sickness

Motion sickness is a state of diminished health characterized by specific symptoms that occur in conjunction with and in response to unaccustomed conditions existing in one's motion environment. These symptoms usually progress from lethargy, apathy, and stomach awareness to nausea, pallor, and cold eccrine perspiration, then to retching and vomiting, and finally to total prostration if measures are not taken to arrest the progression. The sequence of these major symptoms is generally predictable and vestibular scientists have devised a commonly used scale, consisting of five steps from mild malaise to frank sickness, to quantify the severity of motion sickness according to the level of symptoms manifested (67). Under some conditions, however, emesis can occur precipitously, that is, without premonitory symptoms. Other symptoms sometimes seen with motion sickness are headache, increased salivation and swallowing, decreased appetite, eructation, flatulence, and feeling warm. Although vomiting provides temporary relief from the symptoms of motion sickness, the symptoms will return if the offending motion or other condition continues, and the vomiting will be replaced by nonproductive retching or "dry heaves." A wide variety of motions and orientational conditions qualify as offensive, so there are many species of the generic term motion sickness. Among them are seasickness (*mal de mer*), airsickness, car sickness, train sickness, amusement-park-ride sickness, camel sickness, motion-picture sickness, flight-simulator sickness, and the most recent addition to the list, space motion sickness. A variation of motion sickness is the Sopite syndrome where drowsiness is the main symptom and may represent a residual neonatal response similar to rocking a baby to sleep (68).

Adaptation to motion occurs over a period of hours to days. Continuous exposure to motion environments such as in space flight or sea voyages will result in readaptation to the nonmoving environment upon return to land, sometimes resulting in a brief period where the individual continues to experience a false sense of motion, *mal de debarquement* (69–71).

Military Experience

Armstrong (72) has provided us with some interesting statistics on airsickness associated with the World War II military effort:

> . . . it was learned that 10 to 11 percent of all flying students became air sick during their first 10 flights, and that 1 to 2 percent of them were eliminated from flying training for that reason. Other aircrew members in training had even greater difficulty and the airsickness rate among them ran as high as 50 percent in some cases. It was also found that fully trained combat crews, other than pilots, sometimes became air sick which affected their combat efficiency. An even more serious situation was found to exist among air-borne troops. Under very unfavorable conditions as high as 70 percent of these individuals became air sick and upon landing were more or less temporarily disabled at a time when their services were most urgently needed.

More recent studies of the incidence of airsickness in U.S. and U.K. military flight training reveal that approximately 40% of aircrew trainees become airsick at some time during their training. In student pilots, there is a 15% to 18% incidence of motion sickness that is severe enough to interfere with control of the aircraft. Airsickness in student aviators occurs almost exclusively during the first several training flights, during spin training, and during the first dual aerobatic flights. The adaptation which most people are capable of is evidenced by the fact that only approximately 1% of military pilot trainees are eliminated from flight training because of intractable airsickness. The percentage of other aircrew trainees eliminated because of airsickness is considerably higher, however.

Although trained pilots almost never become airsick while flying the aircraft themselves, they surely can become sick while riding as a copilot or as a passenger. Other trained aircrew, such as navigators and weapon systems operators, are likewise susceptible to airsickness. Particularly provocative for these aircrew are flights in turbulent weather, low-level "terrain-following" flights, and flights in which high G forces are repeatedly experienced, as in air combat training and bombing practice. The lack of foreknowledge of aircraft motion, which results from not having primary control of the aircraft, and the lack of a constant view of the external world, which results from having duties involving the monitoring of in-cockpit displays, are significant factors in the development of airsickness in these aircrew.

Simulator Sickness

Flight simulator sickness is getting increased attention now as aircrew spend more and more time in flight simulators capable of ever greater realism. Currently used high-quality military flight simulators are reported to elicit symptoms in 40% to 70% of trainees. Generally, these symptoms are the usual drowsiness, perspiration, and nausea that occur in other forms of motion sickness; vomiting rarely occurs because simulated flights can readily be terminated before reaching the point of emesis. Symptoms associated with eyestrain (headache, blurring of vision) are also quite common. But of particular aeromedical interest is the fact that simulator exposure also frequently results in postflight disturbances of posture and locomotion, transient disorientation, involuntary visual flashbacks, and other manifestations of acute sensory rearrangement.

Simulator sickness is more likely to occur in simulators that employ wide-field-of-view, optical-infinity, computer-generated visual displays, both with and without motion bases, than in those providing less realistic ambient visual stimulation. Helicopter simulators are especially likely to generate symptoms, probably because of the greater freedom of movement available to these aircraft at low altitudes. Interestingly, simulator sickness is more likely to occur in pilots having considerable experience in the specific aircraft that is being simulated than in pilots without such experience. Symptoms usually disappear within several hours of termination of the simulated flight, but a small percentage of subjects have symptoms of disequilibrium persisting as long as 1 day after exposure. Because of the possibility of transient sensory and motor disturbances following intensive training in a flight simulator, it is recommended that aircrew not resume normal flying duties in real aircraft until the day after training in simulators known to be capable of inducing simulator sickness. As is the case with other motion environments, repeated exposure to the simulated motion environment usually renders aircrew less susceptible to its effects. Virtual reality demonstrators as well as theaters designed to create compelling scene movements can produce simulator sickness in the general populace, where it may be termed *cybersickness* (73).

Civil Experience

The incidence of airsickness during flight training of civilians can only be estimated, but is probably somewhat less than that for their military counterparts because the training of civil pilots does not usually include spins and other aerobatics. Very few passengers in the present day commercial air-transport aircraft become airsick, largely because the altitudes at which these aircraft generally fly are usually free of turbulence. This cannot be said, however, for passengers of most lighter, less-capable, general aviation aircraft, who often must spend considerable portions of their flights at the lower, bumpier altitudes.

Space Motion Sickness

The challenges of space flight include coping with space motion sickness, a form of motion sickness experienced first by cosmonaut Titov and subsequently by more than 70% of space crewmembers, primarily during the first 2 or 3 days of the mission (71). The incidence of space motion sickness has been significantly greater in the larger space vehicles (e.g., Skylab, Shuttle), in which crewmembers make frequent head and body movements, than in the smaller vehicles (e.g., Apollo), in which such movements were more difficult. The current incidence remains in the 60% to 80% range. Although space motion sickness resembles other forms of motion sickness, the emesis occurring in space vehicles is not associated with the customary prodromal nausea and cold sweat, but occurs precipitously. This same phenomenon can occur, however, in other novel orientational environments when the level of stimulation is very low and prolonged or very intense and sudden. Because of the similarity between the sudden vomiting associated with space flight and the "projectile" or "avalanche" vomiting frequently seen in patients with increased intracranial pressure, a theory was proposed that the sickness precipitated by space flight was due to a cephalad fluid shift resulting from the zero-G environment. This fluid shift theory is no longer popular, having been replaced by the more conservative consensus that the symptoms generated by space flight have the same origin as those of ordinary motion sickness, hence the commonly accepted terminology "space motion sickness" (74).

The time course of space motion sickness symptom development and resolution is presented graphically in Figure 6-45. Symptoms usually appear within a few minutes to several hours of exposure, plateau for hours to days, and rapidly resolve by 36 hours on average. One feature of space motion sickness that bears special mention is a characteristic adynamic ileus, evidenced by the profound lack of bowel sounds (75). Because of this absence of normal gastrointestinal activity, nutrition is compromised until adaptation occurs. As a consequence of their adaptation to the zero-G environment, some space crew again experience motion sickness upon their return to Earth, although the severity and duration of symptoms tend to be less than experienced during their initial exposure to space. Adapted space crewmembers are also reported to be especially resistant to other forms of motion sickness (e.g., airsickness, seasickness) for up to a few days after returning from space (76). Predicting who will get space motion sickness has not been successful beyond the experience an astronaut had on a previous flight (77).

Space motion sickness has a negative effect on the efficiency of manned space operations, given that 10% to 20% of crewmembers being affected to the point that their performance is significantly impaired for the first few days. Therefore, the potential impact of space motion sickness on manned space operations must be minimized by appropriate mission planning. If possible, duties involving less locomotion should be scheduled early in the flight. Because of the possibility of space motion sickness–induced emesis into a space suit and the consequent risk of life and mission success, extravehicular activity (EVA) should not be undertaken before the third day of a space mission (cite actual flight rule). By that time, adaptation to the novel environment is largely complete, and the head and body movements during EVA are much less likely to provoke symptoms compared to the preadaptation period. Of interest is the fact that pitching motions of the head are the most provocative, followed by rolling and yawing motions, and these motions are more provocative with eyes open than with eyes closed. Those observations suggest that otolith organ–mediated changes in vestibulo-ocular reflex gain during altered gravitational states constitute at least part of the underlying mechanism of space motion sickness (78). Treatment—prophylaxis

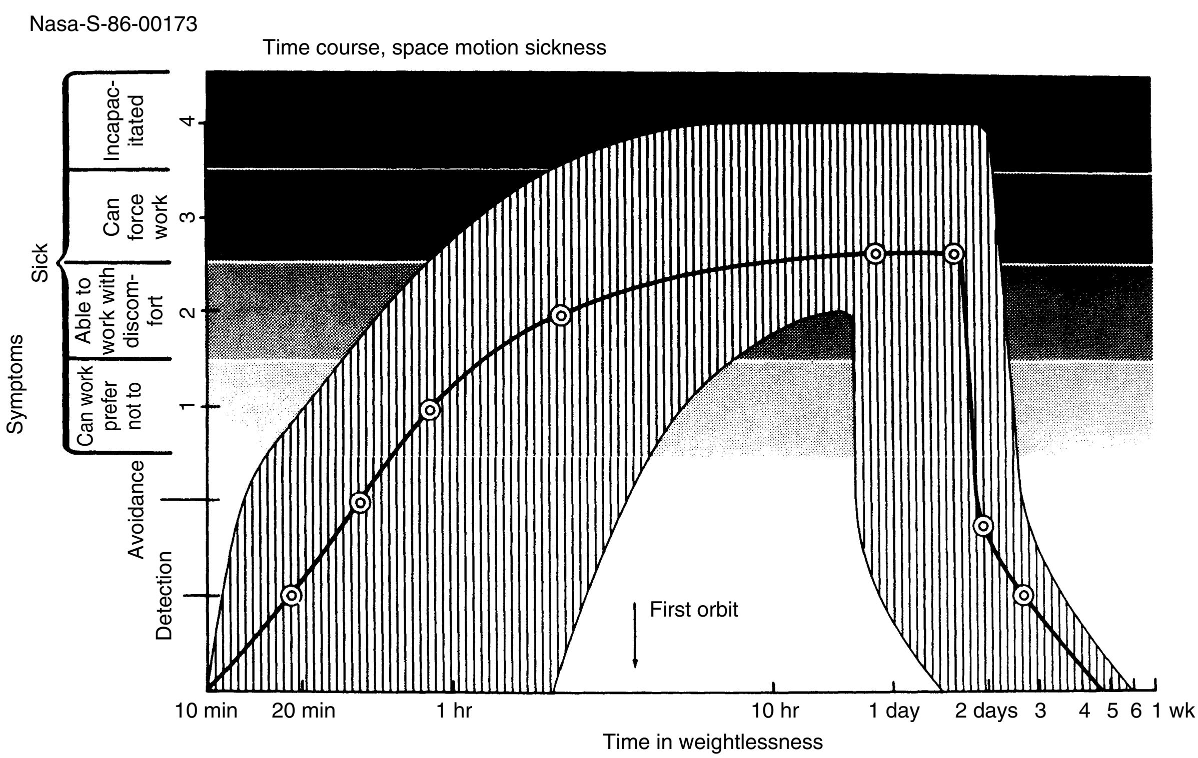


FIGURE 6-45 Time course of space motion sickness symptoms. The shaded area represents the range of symptoms recorded from space shuttle crewmembers.

was tried with scop/dex; then with IM Phenergan (published results). Treatment with pharmaceuticals has been tried with oral scopolamine/d-amphetamine, but was superceded due to side effects by intramuscular and later oral promethazine (71,79).

Another type of space sickness will be encountered in the event that larger space stations are rotated to generate G loading for the purpose of alleviating the fluid shift, cardiovascular deconditioning, and skeletal demineralization that occur in the zero G (76,80).

Etiology of Motion Sickness

We have speculated about the causes of and reasons for motion sickness for thousands of years. We may now have a satisfactory explanation for this puzzling malady because of the scientific interest in motion sickness that has been generated by naval and aerospace activities of the present century.

Correlating Factors

As already mentioned, motion sickness occurs in response to conditions to which one is not accustomed in the normal motional environment. Motional environment means all of the linear and angular positions, velocities, and accelerations that are directly sensed or secondarily perceived as determining one's spatial orientation. The primary quantities of relevance here are mechanically (as opposed to visually) perceived linear and angular acceleration or more specifically those stimuli that act on the vestibular end organs. Certainly, the pitching, rolling, heaving, and surging motions of ships in bad weather are clearly correlated with motion sickness, as are the pitching, rolling, yawing, and positive and negative G pulling of aircraft during maneuvers.

Abnormal stimulation of the semicircular canals alone, as with a rotating chair, can result in motion sickness. Abnormal stimulation of the otolith organs can also result in motion sickness, as occurs in an elevator or a four-pole swing. Whether the stimulation provided is complex, as is usually the case on ships and in aircraft, or simple, such as that generated in the laboratory, the important point is that abnormal labyrinthine stimulation is associated with the production of motion sickness. Not only is a modicum of abnormal vestibular stimulation sufficient to cause motion sickness but some amount of vestibular stimulation is also necessary for motion sickness to occur. Labyrinthectomized experimental animals and humans without functioning vestibular end organs (so-called labyrinthine defectives) are completely immune to motion sickness.

The visual system can play two very important roles in the production of motion sickness. First, self-motion sensed solely through vision (i.e., vection) can make some people sick. Examples of this phenomenon are: motion-picture sickness (wide-screen movies of rides on airplanes), roller coasters, and ships in rough seas, microscope sickness (susceptible individuals cannot tolerate viewing moving microscopic slides), and flight-simulator sickness (wide field-of-view visual motion systems create motion sickness in the absence of any mechanical motion). Abnormal stimulation of ambient vision rather than of focal vision appears to be the essential feature of visually induced motion sickness. The fact that orientation information processed through the ambient visual system converges on the vestibular nuclei helps to reconcile the phenomenon of visually induced motion sickness with the necessity for functioning vestibular end organs. The second role of vision in the etiology of motion sickness is illustrated by the well-known fact that the absence of an outside visual reference makes persons undergoing abnormal motion more likely to become sick than they would be if an outside visual reference were available. Good examples of this are the sailor who becomes sick below deck but prevents the progression of motion sickness by coming topside to view the horizon, and the aircrew who become sick while attending to duties inside the aircraft (e.g., radarscope monitoring) but find symptoms alleviated by looking outside.

Other sensory systems capable of providing primary spatial-orientational information are also capable of providing avenues for motion sickness–producing stimuli. The auditory system, when stimulated by a revolving sound source, is responsible for audiogenic vertigo, audiokinetic nystagmus, and concomitant symptoms of motion sickness. This should not be confused with a pathological condition called the *Tullio phenomena*, where normal sound levels generate vertigo. Perhaps more important than the actual sensory channel employed or the actual pattern of stimulation delivered is the degree to which the spatial-orientational information received deviates from that anticipated. The experience with motion sickness in various flight simulators bears witness to the importance of unexpected patterns of motion and unfulfilled expectations of motion. Instructor pilots in the 2-FH-2 helicopter hover trainer, for example, were much more likely to become sick in the device than were student pilots. It is postulated that imperfections in flight simulation are perceived by pilots who, as a result of their experience in the real aircraft, expect certain orientational stimuli to occur in response to certain control inputs. Pilots without time in the real aircraft, on the other hand, have no such expectations and, therefore, no reference for deviations in the simulator. Another example of the role played by the expectation of motion in the generation of motion sickness is seen in the pilot who does not become sick as long as he or she has control of the airplane but becomes sick when another pilot is flying. In this case, the pilot's expectation of motion is always fulfilled when he or she controlling the airplane but is not fulfilled when someone else is flying.

Several other variables not primarily related to spatial orientation seem to correlate well with motion sickness susceptibility. Age is one such variable; susceptibility increases with age until puberty and then decreases thereafter. Sex is another; younger women are slightly more susceptible to motion sickness than men (two thirds more women become seasick on ocean-going ferry boats, for example, but this may represent a societal reporting phenomena, as under laboratory conditions, the difference in incidence and severity

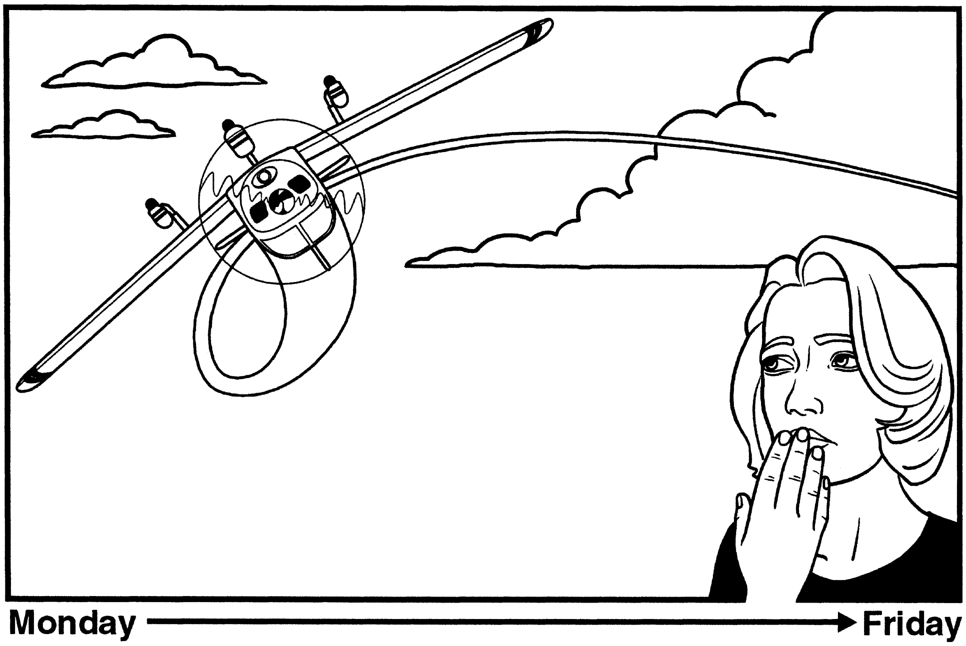


FIGURE 6-46 Conditioned motion sickness. A student aviator who repeatedly gets airsick during flight can become conditioned to develop symptoms in response to the sight or smell of an aircraft even before flight. Use of antimotion sickness medicine until the student adapts to the novel motion can prevent conditioned motion sickness.

is much smaller and the sex difference disappears with age (81,82). In concordance with popular opinion, there is some scientific evidence that having eaten just before motion exposure tends to increase motion sickness susceptibility. There is also evidence suggesting that a high level of aerobic conditioning increases one's susceptibility to motion sickness, possibly as a result of increased parasympathetic tone. The personality characteristics of emotional lability and excessive rigidity are also positively correlated with motion sickness susceptibility. Whether one is mentally occupied with a significant task during exposure to motion or is free to dwell on orientation cues and the state of one's stomach seems to affect susceptibility. The latter, more introspective state is more conducive to motion sickness. Likewise, anxiety, fear, and insecurity, either about one's orientation relative to the ground or about one's likelihood of becoming motion sick, seem to enhance susceptibility. We must be careful, however, to distinguish between sickness caused by fear and sickness caused by motion; a paratrooper who vomits in an aircraft while waiting to jump into battle may be having fear or motion sickness, or both. Finally, it must be recognized that many things, such as mechanical stimulation of the viscera or malodorous aircraft compartments, do not in themselves cause motion sickness, although they are commonly associated with conditions that result in motion sickness.

A mildly interesting but potentially devastating phenomenon is conditioned motion sickness. Just as Pavlov's canine subjects learned to salivate at the sound of a bell, student pilots and other aircrew repeatedly exposed to the conditioning stimulus of sickness-producing aircraft motion may eventually develop the autonomic response associated with motion sickness to the conditioned stimulus of being in or even just seeing an aircraft (Figure 6-46). For this reason, it is advisable to initiate aircrew gradually to the abnormal motions of flight and to provide pharmacologic prophylaxis against motion sickness, if necessary, in the early instructional phases of flight.

Unifying Theory

Current thinking regarding the underlying mechanisms of motion sickness has focused on the "sensory conflict," or "neural mismatch," hypothesis proposed originally by Claremont in 1931. In simple terms, the sensory conflict hypothesis states that motion sickness results when incongruous orientation information is generated by various sensory modalities, one of which must be the vestibular system. In virtually all examples of motion sickness, one can with sufficient scrutiny, identify a sensory conflict. Usually, the conflict is between the vestibular and visual senses or between the different components of the vestibular system. However, conflicts between vestibular and auditory or vestibular and nonvestibular proprioceptive systems are also possible. A clear example of sickness resulting from vestibular–visual conflict occurs when an experimental subject wears reversing prisms over the eyes so that the visual perception of self-motion is exactly opposite in direction to the vestibular perception of it. This also demonstrates the plasticity of the human brain, as adaptation takes place over a few days, and readaptation must occur when use of the prisms ceases. Another example is motion-picture sickness, where conflict arises between visually perceived motion and vestibularly perceived stationary state. Airsickness and seasickness are most often a result of vestibular–visual conflict; the vestibular signals of linear and angular motion are not in agreement with the visual percept of being stationary inside the vehicle. Vestibular–visual conflict need not even be in relation to motion but can be in relation to static orientation. Some people become sick in "antigravity" houses, which are built in such a way that the visually apparent vertical is quite different from the true gravitational vertical.

Intravestibular conflict is an especially potent means of producing motion sickness. When vestibular Coriolis effects cause the semicircular ducts to signal a false angular velocity about a nonvertical axis is occurring, and the otolith organs do not confirm a resulting change in angular position, the likelihood of developing motion sickness is great. In a zero-gravity environment, when an individual makes head movements, the semicircular ducts sense rotation but the otolith organs cannot sense any resulting change of angular position relative to a gravity vector. Many scientists believe the generation of the intravestibular conflict to be the underlying mechanism of space motion sickness.

Conceptually similar is the "otolith-organ tilt-translation reinterpretation" hypothesis, which states that space motion sickness results from a visual–vestibular conflict that occurs until one learns to interpret otolith-organ stimulation in the zero-G condition correctly (i.e., as resulting from linear acceleration rather than from the force of gravity). This model is the basis of a promising scheme to preadapt astronauts to the conflictual sensory effects of the weightless environment (83), but the pharmaceutical approach seems superior (79,80). Another hypothesis is that the altered gain of vestibular-ocular reflexes in microgravity creates conflicts between visually perceived orientation and that perceived through the vestibular sense, or even the anticipated and the actually experienced visual orientations. A more subtle hypothesis is that morphologic asymmetry and/or asymmetric functioning of the left and right otolith organs, for which compensation has occurred in the one-G environment, results in conflicting vestibular orientation information in other than the one-G environment. No matter which explanation of space motion sickness eventually prevails, sensory conflict will likely remain a central theme.

What determines whether orientation information is conflicting or not? One's prior experience in the motional environment and the degree to which the expected orientation information agrees with the actual orientation information received. Therefore, important sensory conflict is not so much an absolute discrepancy between information from the several sensory modalities as it is a discrepancy between anticipated and actual orientation information. Evidence of this can be seen in the gradual adaptation to sustained abnormal motional environments, such as the sea, space, slow rotation room, and prism-reversing environments, and in the readaptation to the normal environment upon return. It has also been demonstrated that anticipating orientation cues confers resistance to motion sickness, as evidenced by the fact that pilots and automobile drivers almost never become sick and by the fact that we actively subject ourselves to many motions (jumping, dancing, and acrobatics) that would surely make us sick if we were subjected to them passively. It appears, then, that the body refers to an internal model of orientational dynamics, both sensory and motor, to effect voluntary and involuntary control over orientation. When transient discrepancies between predicted and actual orientation data occur corrective reflex activity is initiated and/or the internal model is updated. However, when sustained discrepancies occur motion sickness is the result.

Neurophysiology

The neurophysiology of motion sickness remains an enigma, although some progress in this area has been made recently. We now know that the chemoreceptive emetic trigger zone (CTZ) in the lower brainstem is not essential for motion-induced vomiting in experimental animals, as was once believed: therefore, there is more than one pathway to the medullary vomiting center. A popular hypothesis has been that motion sickness results mainly from a stimulated imbalance of lower brainstem neuronal activity, which is normally in a state of dynamic balance between muscarinic cholinergic (parasympathetic) and noradrenergic (sympathetic) activity. Therefore, the focus of attention has been on the vestibular nuclei, reticular formation, and automatic control centers of the lower brainstem.

In support of this hypothesis are observations that scopolamine, a muscarinic cholinergic receptor blocker, and dextroamphetamine, an adrenergically active compound that stimulates norepinephrine release, are highly effective pharmacologic agents for controlling motion sickness, especially in combination. In contrast, neuropharmacologic studies have not demonstrated significant lower brainstem sites of activity of these drugs. Accordingly, there has been speculation that other anatomic structures, in particular the limbic system and basal ganglia, are of critical importance in the development and treatment of motion sickness. Kohl (84) points out that limbic structures are very important in the selection of sensory systems in the mechanisms of attention. Kohl argues that sensory conflict is an essential feature of motion sickness pathogenesis, as well as the profound dependence on vision, which develops with adaptation to a conflict-generating motional environment. Both strongly suggest that limbic attentional mechanisms are heavily involved in the production and resolution of motion sickness. Kohl also argues that the known effects of scopolamine on limbic structures (particularly the septohippocampal tract) and the ability of dextroamphetamine to enhance dopamine transmission (particularly in the nigrostriatal and mesolimbic systems) constitute evidence that limbic structures and the basal ganglia are involved in motion sickness pathogenesis. Kohl and Lewis (85) believe that those structures subserve "a higher sensory integrative process that acts upon sensory discordance and suppresses or activates reflexes which produce autonomic symptomatology." Although the neurophysiology and neuropharmacology of motion sickness and its treatment have not been determined definitively, current evidence removes the important sites of action from the vestibular end organs and lower brainstem and places them in the higher subcortical regions. The importance of vestibular inputs in autonomic regulation is unclear because controls for secondary factors, such as affective/emotional responses and cardiovascular responses elicited by muscle contraction and regional blood pooling, have been inadequate. Anatomic and physiologic evidence of an extensive convergence of vestibular and autonomic information in the brainstem suggests though that there may be an integrated representation of gravitoinertial acceleration from vestibular, somatic, and visceral receptors for somatic and visceral motor control. In the case of vestibular dysfunction or motion sickness, the unpleasant visceral manifestations (e.g., epigastric discomfort, nausea, or vomiting) may contribute to conditioned situational avoidance (86).

Teleology

Even if the mechanism of motion sickness could be described completely in terms of cellular and subcellular functions, the purpose motion sickness serves would still be a mystery. A possible answer is offered by Treisman (87), who proposed that the orientation senses, in particular the vestibular system, serve an important function in the emetic response to poisons. When an animal ingests a toxic substance and experiences effects on the central nervous system, namely, deterioration of the spatial orientation senses and consequent degraded predictability of sensory responses to motor activity, reflex vomiting occurs and the animal is relieved of the poison. The positive survival value of a mechanism eliminating ingested poisons is obvious. The essential nature of vestibular end organs and certain parts of the cerebellum, and the role of sensory conflict as manifested through the function of those structures have provided a rational basis for Treisman's theory. Experimental support for Treisman's theory has been provided by labyrinthectomized animals, who, in addition to being immune to motion sickness, exhibit marked impairment of the emetic response to certain naturally occurring poisons.

Prevention and Treatment of Motion Sickness

The variety of methods at our disposal for preventing and treating motion sickness is not an indication of how easy motion sickness is to control, but is reflective of how incompletely effective each method can be. Nevertheless, logical medical principles are generally applicable; several specific treatments have survived the test of time and become traditionalized, and some newer approaches appear to have great potential.

Physiologic Prevention

An obvious way to prevent motion sickness is to avoid environments that produce it. For most individuals in today's world, however, this is neither possible nor desirable. The most common and ultimately most successful way to prevent motion sickness is to adapt to the novel motional environment through constant or repeated exposures. The rapidity with which adaptation occurs is highly variable and depends mainly on the strength of the challenge and on the adaptability of the individual involved. Usually, several days of sustained exposure to mild orientational challenges (like sea and space travel) or several sessions of repeated exposure to vigorous challenges (such as aerobatics or centrifuge riding) will confer resistance. The use of antimotion sickness medications to prevent symptoms during flight was tried but has been dropped in space flight in general due to the inability to predict the occurrence of space motion sickness (71,77).

An important concept that must be considered when attempting to preadapt passengers or crew to a novel orientational environment is that adaptation to motion appears to have both a general and a specific component (88). The greater the similarity of the stimuli used in the preadaptation regimen to the stimuli expected in the novel environment, the greater the probability of successful adaptation. As a case in point, exposure to high-G aerobatics before zero-G space flight was practiced in an effort to increase resistance to space motion sickness because of a general effect, but failed to yield any positive effect.

The selection of individuals resistant to motion sickness, or screening out those unusually susceptible to it, has been considered as a method for reducing the likelihood of motion sickness in certain operations, such as military aviation training. The fact that susceptibility to motion sickness is such a complex characteristic makes selection less efficacious a means of prevention than might be supposed. At least three separate factors are involved in motion sickness susceptibility: (a) receptivity, the degree to which a given orientational information conflict is perceived and the intensity with which it is experienced and responded to; (b) adaptability, the rate at which one adjusts to an abnormal orientational environment as evidenced by his or her becoming less and less symptomatic; and (c) retention, the ability to remain adapted to the novel environment after leaving it. These factors appear to be independent. This implies that a particular prospective aviator with high receptivity might also very rapidly adapt and remain adapted for a long time, so that it would be unwise to eliminate him or her from flight training on the basis of a history of motion sickness or even a test of susceptibility. Although the great majority of aircrew trainees adapt to the aerial environment, vestibular stimulation tests and motion sickness questionnaires reveal that sensitivity to motion sickness tends to be inversely related to success in flight training. Furthermore, sound judgment dictates that an attempt to select against crewmembers with a high probability of motion sickness is appropriate for some of the more critical and expensive aerospace operations.

Some promising results have been obtained with biofeedback-mediated behavior modification and other methods for desensitizing fliers with chronic airsickness.

Physiologic Treatment

Once symptoms of motion sickness have developed, the first step to bring about recovery is to escape from the environment that is producing the symptoms. If this is possible, relief usually follows rapidly but symptoms can still progress to vomiting, and nausea and drowsiness can sometimes persist for many hours, even after termination of the offending motion. If escape is not possible, assuming a supine position or stabilizing the head seems to offer some relief. As mentioned previously, passengers subjected to motion in enclosed vehicles can help alleviate symptoms by obtaining a view of the natural horizon. One of the most effective physiologic remedies is turning over control of the vehicle to the symptomatic crewmember. Generations of flight instructors have used this technique to avert motion sickness in their students, although they were probably unable to explain how it works in terms of reducing conflict between anticipated and actual orientation cues. Another procedure that has proved useful in practice is to cool the affected individual with a blast of air from the cabin air vent.

Pharmacologic Prevention

The most effective single medication for prophylaxis against motion sickness is scopolamine (0.3–0.6 mg) taken orally 30 minutes to 2 hours before exposure to motion. Unfortunately, the side effects of scopolamine when taken in orally effective doses (i.e., drowsiness, dry mouth, pupillary dilation, and paralyzed visual accommodation) make the routine oral administration of this drug to aircrew highly inadvisable. When prophylaxis is needed for prolonged exposure to abnormal motion (e.g., an ocean voyage), oral scopolamine can be administered every 4 to 6 hours; again, the side effects are troublesome and may preclude repeated oral administration. One approach to the problem of prolonged prophylactic administration of scopolamine is the transdermal therapeutic system (TTS), which delivers 0.5 mg of scopolamine transdermally over a 3-day period from a small patch worn behind the ear. For maximum effectiveness, the patch should be applied at least 8 hours before exposure to the environment that causes sickness. The cognitive, emotional, and visual side effects associated with this route of administration are considerably less than with oral scopolamine. Great care should be taken to clean the hands after application because rubbing the eyes will produce paralysis of accommodation for the next week.

The antimotion sickness preparation most useful for aircrew is the "scop-dex" combination, which is 0.6 mg of scopolamine and 5 or 10 mg of dextroamphetamine taken orally 2 hours before exposure to motion. A second dose of scopolamine, 0.6 mg, and dextroamphetamine, 5 mg, can be given after several hours if needed. Not only is this combination of drugs more effective than scopolamine alone but the stimulant effect of the dextroamphetamine also counteracts the drowsiness provided by the scopolamine. Once commonly used in military flight training, this combination has generally fallen out of use. Because the individual response to the several effective antimotion sickness preparations is variable, it may be worthwhile to perform individual assessments of different drug combinations and dosages to obtain the maximum benefit.

Pharmacologic Treatment

If motion sickness progresses to the point of nausea, and certainly if vomiting occurs, oral medication is useless. If the prospect of returning soon to the accustomed motional environment is remote, it is important to treat the condition to prevent the dehydration and electrolyte loss that result from protracted vomiting. Intramuscular promethazine has been used in treating space motion sickness on space shuttle flights. Microcapsule-gel formulation for intranasal promethazine administration has been considered (89).

Promethazine rectal suppositories are used to control vomiting in many clinical situations, and its use in treatment of motion sickness should be successful. If the parenteral administration of scopolamine or promethazine does not provide relief from vomiting, sedation with intravenous phenobarbital may be necessary to prevent progressive deterioration of the patient's condition. Of course, fluid and electrolyte losses must be replaced in patients who have been vomiting for prolonged periods.

Aeromedical Use of Antimotion Sickness Preparations

Antihistamines, diphenhydramine and meclizine, are highly effective in suppressing nausea and treating motion sickness in passengers. Unfortunately they are also highly sedating and seriously impair cognition. They are strictly contraindicated for several dosing half-lives before any crewmember is to fly in any aircraft or operate any equipment. The nonsedating antihistamines are ineffective in preventing or treating motion sickness and nausea (90,91).

As mentioned previously, the routine use of antimotion sickness drugs in aircrew is not appropriate due to the undesirable side effects of these drugs. Prophylactic medication can be very useful, however, in helping the student aviator cope with the novel motions that can cause sickness during flight training. This promotes better conditions for learning and prevention of conditioned motion sickness. Prophylaxis may also reduce a student's anxiety over becoming motion sick. After using medication, if necessary, for two to three dual training sorties (usually at the beginning of flight training and again during the introduction of aerobatics), student pilots should no longer need antimotion sickness drugs. The use of drugs for solo flight should be forbidden. A more liberal approach can perhaps be taken with other aircrew trainees, such as navigators, because of their greater propensity to become motion sick and their less critical influence on flight safety. Trained aircrew, as a rule, should not use antimotion sickness drugs. An exception to this rule is made for space crewmembers, whose exposure to the zero-gravity condition of space flight is infrequent and premission adaptation by other means cannot be assured. Space crewmembers should be expected to need prophylaxis for reentry into the normal gravitational environment of Earth after a prolonged stay at zero gravity (92). Once adapted to the environment of space, they will need to readapt to Earth, reflecting the plasticity of the human brain.

Airborne troops, who must arrive at the battle zone fully effective, are also candidates for antimotion sickness prophylaxis under certain circumstances, such as prolonged low-level flight in choppy weather. In all such cases, the flight surgeon must weigh the risks associated with the developing motion sickness against the risks associated with the side effects of the antimotion sickness drugs and arrive at a judgment of whether to medicate. Decisions of this sort are the very essence of his or her profession.

UNMANNED AERIAL VEHICLES

Although the concept of remotely controlled aircraft is not new, the successful use of these vehicles has grown significantly since the 1990s. Previously limited to military operations, access to civilian airspace is being considered. A pilot, seated in a ground-based cockpit half a world away, is responsible for controlling an aircraft by remote sensing. The potential for mishap is considerable just from a control perspective. In 2004, a German Luna UAV came within 60 m of a midair collision with a civil Airbus 300 near Kabul, Afghanistan. Plans now exist for full-sized cargo aircraft to operate in civil airspace with a single pilot remotely controlling multiple aircraft. The pilot would take control only during takeoff and landing while the aircrafts' flight management system controls the planes during the remainder of the flight. Remaining oriented and situationally aware in such circumstances has not been fully explored (93) (see Chapters 23 and 27).

CONCLUSION

We see how the recent transition of humans into the aerospace motional environment has introduced us not only to new sensations but also to new sensory demands. If they fail to appreciate the fallibility of their natural orientation senses in the novel environment, pilots can succumb to SD. The tragic effects of SD continue to occur, despite our knowledge of how to prevent this killer. The challenges humans experience when operating in the abnormal environment of flight can be met by recognizing our innate limitations. Pilots can meet the demands of the environment and function effectively if they are prepared. We see also how our phylogenetic heritage, by means of orientational mechanisms, renders us susceptible to motion sickness. That same heritage, however, enables us to adapt to new motional environments. The profound and pervasive influence of our orientation senses in aerospace operations cannot be denied or ignored; through knowledge and understanding, however, it can be controlled.

ACKNOWLEDGMENT

The original author of this chapter, Dr. Kent K. Gillingham was killed in an aircraft accident shortly before the completion of the second edition of this book. His contributions, together with his many other achievements, are a memorial to the life of the USAFs leading expert in the area of spatial disorientation. He is memorialized by the Aerospace Medical Association's annual Gillingham Award.

REFERENCES

1. Antuñano M. *Spatial disorientation: seeing is not believing*. FAA Publication AAM-400-00/1. 2005
2. Parmet AJ. Drain that swamp. *Mil Med* 1986;151(1):60–63.
3. Hixson WC, Niven JI, Correia MJ. *Kinematics nomenclature for physiological accelerations, with special reference to vestibular applications*. Pensacola, Florida: Naval Aerospace Medical Institute, 1966; Monograph 14.
4. Henn V, Young LR, Finley C. Vestibular nucleus units in alert monkeys are also influenced by moving visual fields. *Brain Res* 1974;71:144–149.
5. Dichgans J, Brandt T. Visual-vestibular interaction: effects on self-motion perception and postural control. In: Held R, Liebowitz H, Teuber HL, eds. *Handbook of sensory physiology. Perception*. Volume VIII. Berlin: Springer-Verlag New York, 1978.
6. Andersen GJ. Segregation of optic flow into object and self-motion components: Foundations for a general model. In: Warren R, Wertheim AH, eds. *Perception and control of self-motion*. Hillsdale: Erlbaum, 1990:127–141.
7. Previc FH. Functional specialization in the lower and upper visual fields in humans: Its ecological origins and neurophysiological implications. *Behav Brain Sci* 1990;13:471–527.
8. Liebowitz HW, Dichgans J. The ambient visual system and spatial orientation. In: *Spatial disorientation in flight: current problems*. AGARD-CP-287. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1980.
9. Tredici TJ. Visual illusions as a probable cause of aircraft accidents. *Spatial disorientation in flight: current problems*. AGARD-CP-287. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1980.
10. Sperry RW. Neural basis of the spontaneous optokinetic response preceded by visual inversion. *J Comp Physiol Psychol* 1950;43:482–489.
11. Previc FH. The neuropsychology of 3-D space. *Psychol Bull* 1998;124:123–164.
12. Spoendlin HH. Ultrastructural studies of the labyrinth in squirrel monkeys. *The role of the vestibular organs in the exploration of space*. NASA-SP-77. Washington, DC: National Aeronautics and Space Administration, 1965.
13. Jones GM. Disturbance of oculomotor control in flight. *Aerosp Med* 1965;36:461–465.
14. Mach E. *Fundamentals of the theory of movement perception*. Leipzig: Verlag von Wilhelm Engelmann, 1875.
15. Isaacson W. *Einstein*. New York: Simeon & Schuster, 2007:83–84.
16. Chueng B. Basic Non-visual spatial orientation mechanisms. Chapter 2. In: Previc FH, Ercoline WR, eds. *Spatial disorientation in flight*. AIAA, 2004.
17. Holden M, Ventura J, Lackner JR. Stabilization of posture by precision contact of the index finger. *J Vestib Res* 1994;4:285–301.
18. Lackner JR, Dizio P, Jeka J, et al. Precision contact of the fingertip reduces postural sway of individuals with bilateral vestibular loss. *Exp Brain Res* 1999;126:459–466.
19. Fulgham D, Gillingham K. Inflight assessment of motion sensation thresholds and disorienting maneuvers. Presented at the *Annual*

Scientific Meeting of the Aerospace Association. Washington, DC, May, 1989.
20. Rupert AH. Tactile situation awareness system: proprioceptive prostheses sensory deficiencies. *Aviat Space Environ Med* 2000;71(Suppl 9):A92–A99.
21. Endsley MR, Rosiles SA. Auditory localization for spatial orientation. *J Vestib Res* 1995;5(6):473–485.
22. Gillingham KK. The spatial disorientation problem in the United States Air Force. *J Vestib Res* 1992;2:297–306.
23. Previc FH. Detection of optical flow patterns during low-altitude flight. In: Jensen RA, ed. *Proceedings of the fifth International Symposium on aviation psychology*. Columbus: Ohio State University, 1989:708–713.
24. Peters RA. *Dynamics of the vestibular system and their relation to motion perception, spatial disorientation, and illusions*. NASA-CR-1309. Washington, DC: National Aeronautics and Space Administration, 1969.
25. Jones GM. Vestibulo-ocular disorganization in the aerodynamic spin. *Aerosp Med* 1965;36:976–983.
26. Ercoline WR, Devilbiss CA, Yauchi DW, et al. Post-roll effects on attitude perception: "the Gillingham illusion". *Aviat Space Environ Med* 2000;71(5):489–495.
27. Cohen MM, Crosbie RJ, Blackburn LH. Disorienting effects of aircraft catapult launchings. *Aerosp Med* 1973;44:37–39.
28. Federal Aviation Administration. *General aviation controlled flight into terrain joint safety implementation team: final report*. 2000.
29. McCarthy GW, Stott JRR. In flight verification of the inversion illusion. *Aviat Space Environ Med* 1994;65:341–344.
30. Buley LE, Spelina J. Physiological and psychological factors in "the dark-night takeoff accident". *Aerosp Med* 1970;41:553–556.
31. Martin JF, Jones GM. Theoretical man-machine interaction which might lead to loss of aircraft control. *Aerosp Med* 1965;36:713–716.
32. Wade NJ, Schone H. The influence of force magnitude on the perception of body position. I. Effect of head posture. *Br J Health Psychol* 1971;62(2):157–163.
33. Matthews RSJ. The G-excess effect. *IEEE Trans Rehabil Eng* 2000;19(2):56–58.
34. Chelette TL, Martin EJ, Albery WB. The effect of head tilt on perception of self-orientation while in greater than one G environment. *J Vestib Res* 1995;5:1–17.
35. Schone H. On the role of gravity in human spatial orientation. *Aerosp Med* 1964;35:764–722.
36. Correia MJ, Hixson WC, Niven JI. On predictive equations for subjective judgments of vertical and horizon in a force field. *Acta Otolaryngol Suppl* 1968;230:1–20.
37. Matthews RSJ, Previc F, Bunting A. USAF spatial disorientation survey. *Spatial disorientation in military vehicles: causes, consequences and cures*. RTO-MP-086. Neuilly-sur-Seine Cedex, France: North Atlantic Treaty Organization Research and Technology Organisation, 2002:7-1–7-3.
38. *Air force instruction 11-217*. Vol. 1. *Instrument flight procedures*. Washington, DC: Department of the Air Force, Headquarters US Air Force, December 29, 2000.
39. McNaughton G. *Proceedings of the aircraft attitude awareness workshop*. Wright-Patterson AFB, Ohio: Air Force Flight Dynamics Laboratory, 1987.
40. Boeing Commercial Airplane Group. *Statistical summary of commercial jet airplane accidents, worldwide operations 1959–2000*. http://www.boeing.com/news/techissues/pdf/2000/statsum.pdf. 2001.
41. Neubauer JC. Classifying spatial disorientation mishaps using different definitions. *IEEE Trans Rehabil Eng* 2000;19(2):28–34.
42. Davenport C. Spatial Disorientation, the USAF Experience FY 1991–FY 2000. Presentation at *Recent Trends in Spatial Disorientation Research Symposium*. San Antonio, Texas, November 15–17, 2000.
43. Nuttall JB, Sanford WG. *Spatial disorientation in operational flying*. Publication M-27-56. California: United States Air Force Directorate of Flight Safety Research, Norton Air Force Base, Sept. 12, 1956.
44. Moser R. Spatial disorientation as a factor in accidents in an operational command. *Aerosp Med* 1969;40:174–176.
45. Barnum F, Bonner RH. Epidemiology of USAF spatial disorientation aircraft accidents, 1 Jan. 1958–31 Dec. 1968. *Aerosp Med* 1971;42:896–898.
46. Kellogg RS. *Letter report on spatial disorientation incidence statistics*. From The Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. Mar 30, 1973.
47. Knapp CJ, Johnson R. F-16 class a mishaps in the U.S. Air Force, 1975–93. *Aviat Space Environ Med* 1996;67(8):777–783.
48. Collins DL, Harrison G. Spatial disorientation episodes among F-15C pilots during Operation Desert Storm. *J Vestib Res* 1995;5(6):405–410.
49. Cheung B, Money K, Wright H, et al. Spatial disorientation implicated accidents in Canadian Forces, 1982–95. *Aviat Space Environ Med* 1995;66(6):579–585.
50. Singh B, Navathe PD. Indian Air Force and world spatial disorientation accidents: a comparison. *Aviat Space Environ Med* 1994;65(3):254–256.
51. Brathwaite MG, Douglass PK, Durnford SJ, et al. Hazard of spatial disorientation during helicopter flight using night vision devices. *Aviat Space Environ Med* 1998;69(11):1038–1044.
52. NASA. USAF progress on panoramic goggles. *Aviat Week Space Technol* 2000;153(7):56.
53. Lyons TJ, Freeman JE. Spatial disorientation (SD) mishaps in the U.S. Air Force 1988 [abstract]. *Aviat Space Environ Med* 1990;61:459.
54. *The Naval Safety Center Aeromedical Newsletter*. Number 90B3. Norfolk, Virginia: Naval Safety Center, 1990.
55. Scott WB. New research identifies causes of CFIT. *Aviat Week Space Technol* 1996;144(25):70–71.
56. Commercial Aircraft Accident Statistics. *Aviat Week Space Technol* 1999. 151(7); 52–53.
57. Kirkham WR, Collins WE, Grape PM, et al. Spatial disorientation in general aviation accidents. *Aviat Space Environ Med* 1978;49:1080–1086.
58. Shappell SA, Wiegmann DA. *Human error analysis of general aviation controlled flight into terrain accidents occurring between 1990–98*. Washington, DC: FAA Office of Aerospace Medicine, 2003; DOT/FAA/AM-0374.
59. Parmet AJ. Controlled flight into terrain-lessons for general aviation. *Aerospace Medical Association Annual Scientific Meeting*, May 15, 2007.
60. Malcolm R, Money KE. Two specific kinds of disorientation incidents: Jet upset and giant hand. In: Benson J, ed. *The disorientation incident. Part 1*. AGARD-CP-95. Neuilly-sur-Seine, France: North Atlantic Treaty Organization, 1972.
61. Lyons TJ, Simpson CG. The giant hand phenomenon. *Aviat Space Environ Med* 1990;60:64–66.
62. Ocker WC, Crane CJ. *Blind flight in theory and practice*. San Antonio, TX: Naylor, 1932.
63. Wick RL. No flicker vertigo. Letter to the editor. *Business/Commercial Aviat* 1982;51:16.
64. Clark B, Nicholson M, Graybiel A. Fascination: a cause of pilot error. *J Aviat Med* 1953;24:429–440.
65. Clark B, Graybiel A. The break-off phenomenon-a feeling of separation from the Earth experience by pilots at high altitude. *J Aviat Med* 1957;28:121–126.
66. New head-up tool aims to cut runway incidents/FAA top 10 list targets runway safety. *Aviat Week Space Technol* 2000; 153(7):48–51.
67. Miller EF II, Graybiel A. Comparison of five levels of motion sickness severity as the basis for grading susceptibility. *Aerosp Med* 1974;45:602–609.
68. Graybiel A, Knepton J. Sopite syndrome: a sometimes sole manifestation of motion sickness. *Aviat Space Environ Med* 1976;47(8):873–882.

69. Shupak A, Gordon CR. Motion sickness: advances in pathogenesis, prediction, prevention, and treatment. *Aviat Space Environ Med* 2006;77(12):1213–1223.
70. DeFlorio PT, Silbergleit R. Mal de debarquement presenting in the Emergency Department. *J Emerg Med* 2006;31(4):377–379.
71. Jennings RT. Managing space motion sickness. *J Vestib Res* 1998;8(1):67–70.
72. Armstrong HG. Air sickness. In: Armstrong HG, ed. *Aerospace medicine*. Baltimore: Williams & Wilkins, 1961.
73. Lo WT, So RH. Cybersickness in the presence of scene rotational movements along different axes. *Appl Ergon* 2000;32(1):1–14.
74. Lackner JR, Dizio P. Space motion sickness. *Exp Brain Res* 2006;175(3):377–399. Epub 2006 Oct 5.
75. Muth ER. Motion sickness and space sickness: intestinal and autonomic correlates. *Auton Neurosci* 2006;129(1–2):58–66. Epub 2006 Sep 6.
76. Heer M, Paloski. Space motion sickness: incidence, etiology, countermeasures. *Auton Neurosci* 2006;129(1–2):77–79. Epub 2006 Aug 28.
77. Golding JF. Motion sickness susceptibility. *Auton Neurosci* 2006;129(1–2):67–76. Epub 2006 Aug 23.
78. Lackner JR, Graybiel A. Head movements in low and high gravitoinertial force environments elicit motion sickness: implications for space motion sickness. *Aviat Space Environ Med* 1987;58:A212–A217.
79. Davis JR, Jennings RT, Beck BG. Comparison of treatment strategies for space motion sickness. *Acta Astronaut* 1993;29(8):587–591.
80. Yang Y, Kaplan A, Pierre M, et al. Space cycle: a human-powered centrifuge that can be used for hypergravity resistance training. *Aviat Space Environ Med* 2007;78(1):2–9.
81. Bos JE, Damala D, Lewis C, et al. Susceptibility to seasickness. *Ergonomics* 2007;50(6):890–901.
82. Park HS, Hu S. Gender differences in motion sickness history and susceptibility to optokinetic rotation-induced motion sickness. *Aviat Space Environ Med* 1999;70(11):1077–1080.
83. Parker DE, Reschke MF, von Gierke HE, et al. Effects of proposed preflight adaptation training on eye movements, self-motion perception, and motion sickness: a progress report. *Aviat Space Environ Med* 1987;58:A42–A49.
84. Kohl RL. Mechanisms of selective attention and space motion sickness. *Aviat Space Environ Med* 1987;58:1130–1132.
85. Kohl RL, Lewis MR. Mechanisms underlying the antimotion sickness effects of psychostimulants. *Aviat Space Environ Med* 1987;58:1215–1218.
86. Balaban CD. Vestibular autonomic regulation (including motion sickness and the mechanism of vomiting). *Curr Opin Neurol* 1999;12(1):29–33.
87. Treisman M. Motion sickness: an evolutionary hypothesis. *Science* 1977;197:493–495.
88. Dobie TG, May JG. Generalization of tolerance to motion environments. *Aviat Space Environ Med* 1990;61:707–711.
89. McDonough JA, Persyn JT, Nino JA, et al. Microcapsule-gel formulation of promethazine HCl for controlled nasal delivery: a motion sickness medication. *J Microencapsul* 2007;24(2):109–116.
90. Cohen AF, Posner J, Ashby L, et al. A comparison of methods for assessing the sedative effects of diphenhydramine on skills related to car driving. *Eur J Clin Pharmacol* 1984;27(4):477–482.
91. Weiler JM, Bloomfield JR, Woodworth GG, et al. Effects of fexofenadine, diphenhydramine, and alcohol on driving performance. *Ann Droit Int Med* 2000;132(5):354–363.
92. Payne MW, Williams DR, Trudel G. Space flight rehabilitation. *Am J Phys Med Rehabil* 2007;86(7):583–591.
93. Hughes D. ATC and UAVS: file-and-fly wannabes. *Aviat Week Space Technol* 2007;166(7):46–53.

CHAPTER 7

Thermal Stress

Robert W. Kenefick, Samuel N. Cheuvront, John W. Castellani, and Catherine O'Brien

INTRODUCTION

In the past, aviators in open cockpit aircraft had to perform flight tasks with little or no protection from the environment or protective systems to mitigate environmental stresses. With the advent of modern aircraft, protective clothing, and survival equipment, it would seem that thermal stress (heat or cold) would no longer be a significant concern for the modern aviator. However, present day protective systems and equipment used in aviation create new situations where aviators remain challenged by thermal stress. For example, closed cockpits can create heat stress due to the greenhouse effect from solar radiation. Protective clothing [G-suits, nuclear-biological-chemical (NBC) gear] add to the difficulty of performing a task and increase heat stress and the risk of dehydration. The proximity of flight crews or ground crews to heat generated by engines and/or reflected from the tarmac or flight deck is also of great concern. This heat stress is further exacerbated by the ambient environment itself when working (ground crews) or waiting outdoors (flight crews) during preflight, taxiing, or standby for takeoff. The combined effects of heat stress and dehydration over many hours for both ground and flight crews can alter cognitive function, delay reaction time, increase error rate, deteriorate physical stamina, impair cockpit management, and increase the risk of heat illness or injury. Although heat mitigation systems exist (air-conditioning, built-in clothing cooling systems), their cooling capacity is limited.

Ground crews and support personnel may also be exposed to cold climates. As with heat, exposure to cold for longer periods can degrade cognitive function such as decision making and physical performance, including manual dexterity, and can increase risk of injury. This is especially true for ground crews who are not only exposed to cold air but also use their hands to perform tasks, where heat loss can occur when touching metal tools, and may lose heat through their feet by standing on a cold tarmac or flight deck for long periods. In these scenarios, risk for frostbite and freezing injuries can be of concern, especially in the extremities (fingers, toes). Heat loss and the risk of cold injury are further aggravated by environmental factors such as wind and/or rain that increase the rate of body heat loss. Flight crews must also be concerned with cold environments during in-flight operations on aircraft with high airflows such as helicopters operating with open doors (Figure 7-1).

FIGURE 7-1 Aerospace personnel may be exposed to low ambient temperatures both during flight and upon planned or unplanned landings in cold climates.

The protection from the environment (cold or heat) afforded by the aircraft is lost when pilots are forced to land or ditch. Once on the ground or in the water, flight crews are fully exposed and a large part of survival depends on meeting environmental challenges. Understanding the factors that contribute to heat gain or heat loss, dehydration, and injury due to environmental exposure can be important not only for ground and flight crews but also for aeromedical personnel who must not only recognize signs of heat or cold injury and dehydration but must also be able to provide appropriate medical treatment. This chapter will outline the specifics regarding mechanisms of heat exchange, the physiological and cognitive responses to environmental stress and dehydration, guidance for operations in hot and cold environments, and will present the signs and symptoms of injuries and illnesses related to heat and cold exposure and provide treatment recommendations.

Biophysics of Heat Exchange

Changes in body core temperature are the result of either a positive or negative change in heat storage. If the body gains more heat than it dissipates, body core temperature will rise. Conversely, if heat loss exceeds heat gain, then heat storage will be negative and core temperature will fall. We can present these relationships between gain and loss mathematically as follows:

$$S = M - (\pm \text{Work}) - E \pm (R + C) \pm K$$

where S = heat storage, M = metabolic heat production, E = evaporation, R = radiation, C = convection, K = conduction, and W = external work (1). E, R, C, and K are the heat exchange pathways, explained in detail in the subsequent text. The mathematical equation contains positive and negative signs that indicate heat gain (positive sign) and heat loss (negative sign). It is important to understand that heat gain or loss by some of these exchange pathways are mathematical. Situations such as negative work ($-W$) may not occur in "real world" applications. Examples of heat gain and storage while on the ground and in the cockpit are depicted in Figures 7-2 and 7-3.

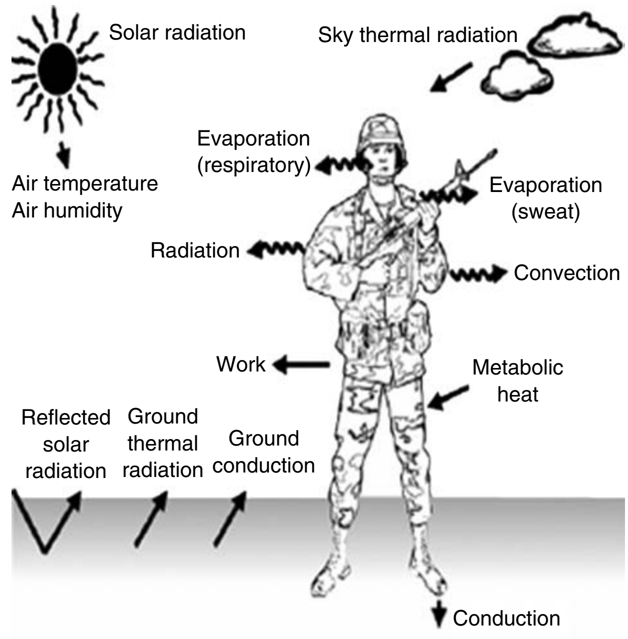


FIGURE 7-2 Sources of environmental cooling or heating on the ground.

During physical work, approximately 25% of energy expended goes toward performing the actual work and approximately 75% of energy expended is released in the form of heat. This heat is released from active skeletal muscles and transferred from the body core to skin, which then must dissipate the heat to the environment. Physical exercise can increase whole body metabolism by as much as 15 to 20 times above the resting metabolic rate in healthy young males. If heat production is not balanced by loss, body temperature will increase early in the work bout. In the cold climate, the opposite scenario occurs, where resting individuals must increase overall resting metabolic

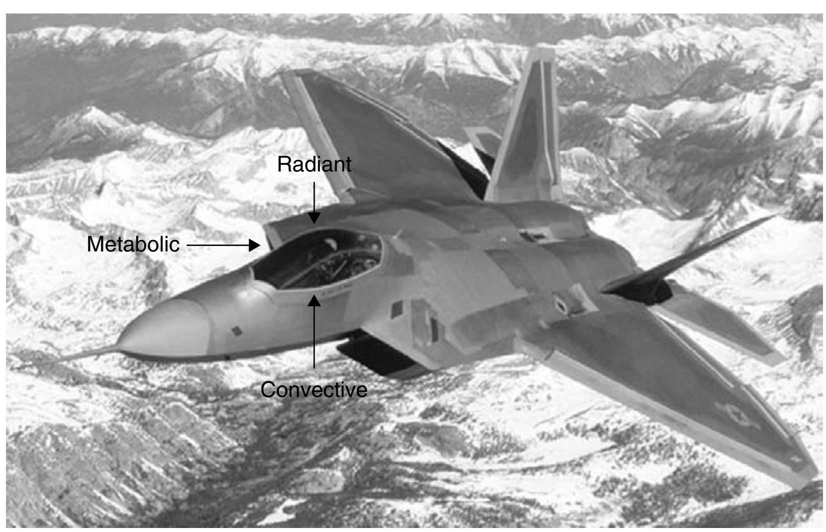


FIGURE 7-3 Examples of cockpit heat sources. Radiative heat from sun and electrical equipment; convective heat from air within cockpit and greenhouse effect; metabolic heat from pilot(s).

heat production (M) through mechanisms such as shivering, which can increase M by 3 to 5 times, in order to maintain normal body core temperature (37°C).

Convection is heat transfer by movement of air or fluid over the body, whether induced by thermal currents, body motion, or natural movement of air (wind) or water. Heat loss by convection occurs when the temperature of the air or water that is in contact with skin is below body temperature; conversely, heat gain by convection from air or water occurs when these temperatures approach or exceed that of the body. The primary means of moving heat from the core to the skin is by convection through blood flow (1).

Heat gain by radiation (solar, sky, large objects, and ground) occurs when radiative temperatures are higher than the body surface temperature. Heat loss occurs when surrounding objects or environments have temperatures lower than the body and the body will radiate heat to these objects and environments. Accordingly, temperature combinations of the sky, ground, and surrounding objects may exist which results in body heat gain due to radiation, although the air temperature is below that of the body. Radiative heat exchange is independent of air motion (1).

Conduction is heat transfer to or from solid objects through direct contact. In hot environments, conduction is usually minimal because little contact surface is involved. However, in the case of individuals such as aircrew, conduction can be more significant due to such factors as standing on hot tarmac, or contact with metal aircraft. Conversely, in the cold standing on cold tarmac, or a steel flight deck can result in conductive heat loss and contributes to extremity cooling.

When the ambient temperature is greater than or equal to skin temperature, evaporative heat loss accounts for all body cooling. Eccrine sweat glands secrete fluid onto the skin surface permitting evaporative cooling when liquid is converted to water vapor. Sweat glands respond to thermal stress primarily through sympathetic cholinergic stimulation, with catecholamines having a smaller role in the sweat response (2). The rate of sweat evaporation depends on air movement and the water vapor pressure gradient between the skin and the environment, so in still or moist air the sweat does not evaporate readily and collects on the skin. Sweat that drips from the body or clothing provides no cooling benefit.

The mechanism of heat loss depends on the ambient temperature. At low ambient temperatures (5°C—10°C), dry heat loss (i.e., heat loss from radiation and convection) is greater than heat loss through evaporation. At high ambient temperatures, evaporative heat loss predominates. Ambient water vapor pressure (relative humidity) also affects heat loss. When water vapor pressure is high, less sweat is able to evaporate from the skin to the environment, compared to a dry environment. Heat exchange between skin (or man) and the environment is influenced by air temperature; air humidity; wind speed; solar, sky, and ground radiation; and clothing.

Physiological Regulation in Hot Environments

Humans regulate their body core temperature within a narrow range (35°C–41°C). This is accomplished through behavioral and physiological regulation. Behavioral thermoregulation includes conscious actions such as altering physical activity, selecting appropriate clothing, adjusting indoor thermostats, and seeking shade, sun, or shelter. Physiological temperature regulation is typically independent of conscious behavior, but can be modified by it, and includes control of skin blood flow (Figure 7-4), sweating, and metabolic heat production (2).

Figure 7-4 schematically depicts the sensory and effector aspects of the human thermoregulatory system. Core temperature is the controlled variable under most conditions and must be maintained within defined limits. Signals regarding core temperature are integrated with skin temperature signals at the hypothalamus. If the core temperature signal deviates from the defined set point, appropriate effector responses (e.g., vasoconstriction or dilation, sweating or shivering) are elicited to either reduce or increase peripheral heat loss and metabolic heat production. For example, during exercise in the heat, core temperature is increased. This change in core

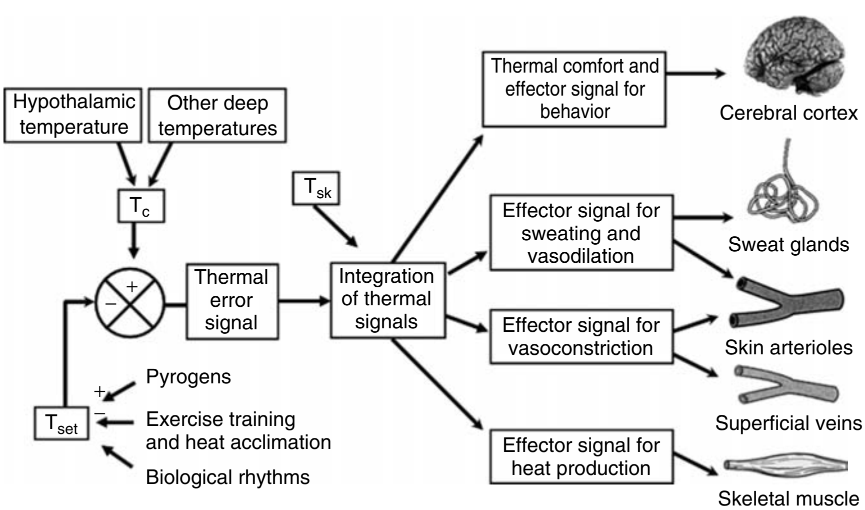


FIGURE 7-4 Schematic of human thermoregulatory control. Sawka MN, Young AJ. Physiological systems and their responses to conditions of heat and cold. In: Tipton CM, ed. *ACSM's advanced exercise physiology*. Philadelphia: Lippincott Williams & Wilkins, 2006:535–563.

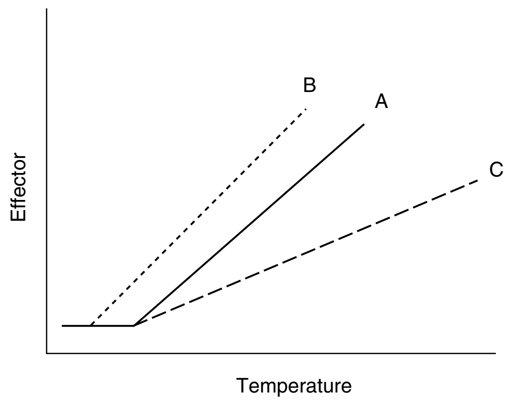


FIGURE 7-5 Proportional control system for two heat-dissipating effector responses (sweating and skin blood flow). Line A: This line demonstrates that the effector response increases as a function of temperature with a characteristic point where the response turns on (threshold) and the response increases as the temperature rises (slope or sensitivity). Line B: Change in the threshold (relative to A) of the effector response with no change in the slope. Line C: Change in the slope of the effector response (relative to A) with no change in the threshold.

temperature causes heat loss effector responses (sweating, vasodilation, and increased skin blood flow) to attenuate the rise in core temperature. These responses exhibit two control characteristics: (i) they turn on when reaching a particular core temperature threshold, and (ii) they exhibit a graded response as the controlled variable is further disturbed. This type of control system is called a *proportional control system*.

Figure 7-5 demonstrates the proportional control system for two heat-dissipating responses (sweating and skin blood flow). Note that there is a particular threshold when these physiological responses increase and then as the core temperature continues to rise, these responses increase linearly. Changes in the threshold of an effector response are generally thought of as a change in the set-point temperature (2). Any change in the slope of the relationship between core temperature and the effector response is considered as a change in the sensitivity of the system at a peripheral level (e.g., sweat gland). For example, dehydration will increase the body core temperature threshold for sweating, thereby delaying the onset of sweating.

Proportional control systems are modified by both thermal and nonthermal factors (3). Skin temperature, a thermal factor, changes the sensitivity of the relationship between sweating and core temperature. Therefore, at any given core temperature, sweat rates are greater when the skin is warm and lower when the skin is cool. Nonthermal factors that change the relationship between core temperature and heat loss responses include dehydration, acclimatization, circadian rhythms, and endocrine status (3,4). Table 7-1 presents the effects of these factors on thermoregulatory control of the heat.

Heat acclimatization is a classic example of how changes in thermoregulatory control impact overall health and performance. Sweating begins at a lower core temperature threshold, allowing earlier heat dissipation and a cooler skin temperature. Similarly, skin blood flow is higher at any given core temperature due to change in the threshold temperature at which cutaneous vasodilation begins to rise (5). Therefore, lower skin temperatures following heat acclimation reduce the volume of skin blood flow for heat exchange; however, acclimation initiates skin blood flow sooner so that dry heat loss (R + C) improves to an even greater extent. Higher sweating rates and skin blood flow, in concert, help explain why core temperature is lower after acclimatization; it is due to better evaporative, radiative, and convective heat loss.

Physiological Regulation in Cold Environments

One of the initial responses to cold exposure is peripheral vasoconstriction. Decreased blood flow to the shell (skin, subcutaneous fat, and skeletal muscle) in effect increases insulation, and reduces convective heat transfer between the body's core and shell (Figure 7-6), and skin temperature declines. Skin vasoconstriction begins when skin temperature falls below 33°C (95°F). As exposure to cold continues, vessels in underlying tissues vasoconstrict and thereby increase the insulating layer. Cooling of underlying inactive muscles can cause them to become stiff. Therefore, the vasoconstrictor

TABLE 7-1

Effect of Nonthermal Factors on Sweating and Skin Blood Flow Threshold and Sensitivity

	Sweating		*Skin Blood Flow*	
Factor	*Threshold*	*Sensitivity*	*Threshold*	*Sensitivity*
Dehydration	Increase	Decrease	Increase	Decrease
Acclimatization	Decrease	Increase	Decrease	Increase
Circadian rhythm	Increased at 4:00 pm and 8:00 PM vs. 12:00 AM and 4:00 AM	No time of day difference	Increased at 4:00 PM and 8:00 PM vs. 12:00 AM and 4:00 AM	Increased slope at 4:00 AM vs. 12:00 AM
Menstrual cycle phase	Higher during luteal phase vs. follicular phase	No difference between follicular and luteal phases	Higher during luteal phase vs. follicular phase	No difference between follicular and luteal phases

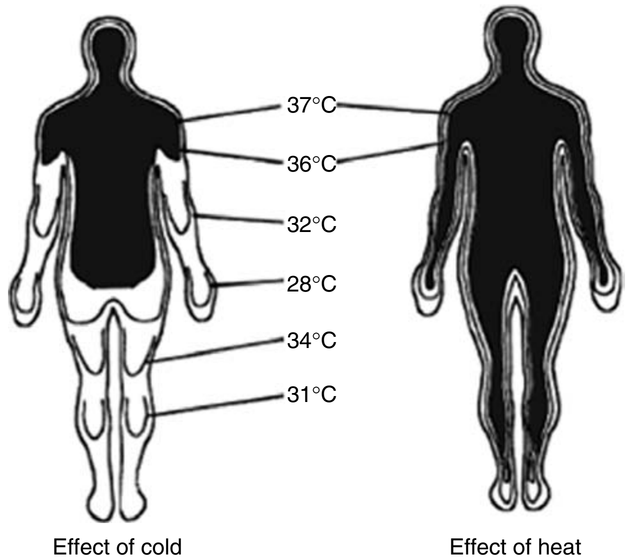


FIGURE 7-6 Effect of heat and cold on skin temperatures.

response to cold exposure helps retard heat loss and defend core temperature, but at the expense of a decline in peripheral tissue temperatures (6).

Another primary response to cold exposure is involuntary shivering, which increases metabolic heat production and voluntary behavior, that is, increasing physical activity (exercise, increased "fidgeting," etc.) which increases heat production. Shivering consists of involuntary, repeated, rhythmic muscle contractions (7), and may start immediately, or after several minutes of cold exposure, usually beginning in torso muscles and then spreading to the limbs (8). The intensity and extent of shivering varies according to the severity of cold stress. As shivering intensity increases and more muscles are involved metabolic rate increases, typically reaching approximately 600 to 700 mL/min during resting cold air exposure, and often exceeding 1,000 mL/min during resting cold water immersion (6). The highest oxygen intake reported is 2.2 L/min, recorded during cold water immersion, which was approximately six times the resting metabolic rate (50% $\dot{V}O_{2max}$) for that subject (9).

A common response to cold exposure is cold-induced diuresis (CID), an increase in urine production associated with the central fluid shift induced by vasoconstriction (10). The fluid loss due to CID does not have the same effects on health and performance during cold exposure as a similar loss of fluid would during heat exposure. In fact, individuals who are dehydrated before cold exposure typically experience less CID than euhydrated individuals (11), that is, the diuresis is self-limiting. Furthermore, individuals who have free access to food and fluid will rehydrate upon returning to a warm environment. The fluid loss due to CID may be more important during heavy exercise in the cold environment when core temperature is elevated and blood flow to the skin increases to dissipate heat. If individuals in the cold environment are heavily clothed, they may overheat more readily and increase fluid losses due to thermoregulatory sweating. For these reasons, maintaining hydration is important during work in cold environments. Dehydration does not appear to increase risk of peripheral cold injury (11).

The vasoconstriction-induced reduction in blood flow and fall in skin temperature contribute to the etiology of peripheral cold injuries, particularly in the digits, ears, cheek, and nose. Cold-induced vasoconstriction has pronounced effects on the hands, fingers, and feet making them particularly susceptible to cold injury, pain, and a loss of manual dexterity (12) (Figure 7-6). Another vasomotor response, cold-induced vasodilatation (CIVD), can under some circumstances interrupt vasoconstriction in the fingers, toes, nose, cheeks and ears. Following the initial decline in skin temperature during cold exposure, an increase in blood flow may occur. The CIVD may be transient, resulting in periodic oscillations of skin temperature. The increased blood flow increases local tissue temperature and may protect against cold injury. Although initiated by local cooling, the CIVD response is also modulated by the central nervous system (13).

Wet Bulb Globe Temperature

Numerous environmental indices have been proposed for predicting thermal heat strain. The most widely used of these is the Wet Bulb Globe Temperature (WBGT) index, which was developed 50 years ago to provide guidance for controlling heat casualties among military troops in hot environments (14). Since this time, the index has also been adopted and popularized by occupational and sports governing authorities to promote safe environmental limits for work and exercise. The WBGT index is computed from measures of the natural wet-bulb temperature (Twb), black globe temperature (Tbg), and dry bulb air temperature (Tdb) using the following weighted formula:

$$\text{WBGT} = 0.7\ (\text{Twb}) + 0.2\ (\text{Tbg}) + 0.1\ (\text{Tdb})$$

When indoors the formula simplifies to 0.7 (Twb) + 0.3 (Tbg). The equation emphasizes the strong influence of air water vapor content on human thermoregulation (sweat evaporation) in the heat, which is an extension of the same fundamental observation made more than a century ago (15). Because NBC protective clothing and body armor create situations where sweat evaporation is impaired, WBGT adjustments for clothing have also been established for the military (16).

In an effort to develop a thermal strain index specifically applicable to aviation, Harrison et al. (17) examined the relationship between ground weather and cockpit conditions across a broad range of WBGT at altitudes less than 3,000 ft. The following equation was developed from the relationship between ground WBGT (WBGTgr) and cockpit WBGT (WBGTcp):

$$\text{WBGTgr} = (\text{WBGTcp} - 0.333)/1.183$$

On the basis of WBGTgr and WBGTcp relationship, a practical thermal strain index for aviation was developed known as the *Fighter Index of Thermal Stress* (FITS) (18). The FITS assumes that Tbg is greater than Ta by 10°C (clear skies) and requires only two ground measurements to estimate cockpit thermal stress:

$$\text{FITS} = 0.83\,(\text{Twb}) + 0.35\,(\text{Ta}) + 5.08$$

FITS temperatures between 32°C and 38°C represent a "caution zone" where operations are permissible for pilots when adhering to proper precautions (18). FITS temperatures greater than 38°C represent a "danger zone" for flight operations that recommend cancellation of low-altitude missions and strict limits on high-altitude flights (18). It is important to remember that FITS provides only general guidance, but it does specifically address the unique occupational circumstances of aviators.

The following FITS procedures are designed to minimize heat stress impact (18):

1. FITS caution zone (between 32°C and 38°C)
   a. Encourage crews to drink water before cockpit entry, during standby, and in flight
   b. Be alert to symptoms of heat stress
   c. Avoid exercise 4 hours before takeoff
   d. Precool cockpits by means of air-conditioning the ground carts
   e. Assign alternate crewmembers to perform preflight aircraft inspection
   f. Keep the sun out of transparencies by using rolling roofs or fabric covers
   g. Transport crewmembers directly to the aircraft
   h. Limit the permitted duration of in-cockpit standby
2. FITS danger zone (temperatures >38°C)
   a. Keep the sun out of transparencies by using rolling roofs or fabric covers
   b. Allow only one change of aircraft before requiring return to ready room in cases of mechanical delay
   c. Optimized conditions for cooling and rehydration between flights
   d. Support self-assessment and empower crews to stand down when they judge that further flights would be unsafe

Wind Chill

Another environmental index that takes into account the cooling that can occur due to convectional flow of air is the Wind Chill Temperature (WCT) index (Table 7-2). The WCT integrates wind speed and air temperature to provide an estimate of the cooling power of the environment, as compared to calm conditions (19). Wind speed may vary locally depending on terrain features, but can also be increased during flight such as helicopter transport with open bays. Wind does not cause an object to become cooler than the ambient temperature, but causes objects to cool toward

TABLE 7-2

Wind Chill Temperature Index Frostbite Times are for Exposed Facial Skin

Wind Speed (mph) ↓	*Air Temperature (°F)*																	
	40	**35**	**30**	**25**	**20**	**15**	**10**	**5**	**0**	**–5**	**–10**	**–15**	**–20**	**–25**	**–30**	**–35**	**–40**	**–45**
5	36	31	25	19	13	7	1	–5	–11	–16	–22	–28	–34	–40	–46	–52	–57	–63
10	34	27	21	15	9	3	–4	–10	–16	–22	–28	–35	–41	–47	–53	–59	–66	–72
15	32	25	19	13	6	0	–7	–13	–19	–26	–32	–39	–45	–51	–58	–64	–71	–77
20	30	24	17	11	4	–2	–9	–15	–22	–29	–35	–42	–48	–55	–61	–68	–74	–81
25	29	23	16	9	3	–4	–11	–17	–24	–31	–37	–44	–51	–58	–64	–71	–78	–84
30	28	22	15	8	1	–5	–12	–19	–26	–33	–39	–46	–53	–60	–67	–73	–80	–87
35	28	21	14	7	0	–7	–14	–21	–27	–34	–41	–48	–55	–62	–69	–76	–82	–89
40	27	20	13	6	–1	–8	–15	–22	–29	–36	–43	–50	–57	–64	–71	–78	–84	–91
45	26	19	12	5	–2	–9	–16	–23	–30	–37	–44	–51	–58	–65	–72	–79	–86	–93
50	26	19	12	4	–3	–10	–17	–24	–31	–38	–45	–52	–60	–67	–74	–81	–88	–95
55	25	18	11	4	–3	–11	–18	–25	–32	–39	–46	–54	–61	–68	–75	–82	–89	–97
60	25	17	10	3	–4	–11	–19	–26	–33	–40	–48	–55	–62	–69	–76	–84	–91	–98

Frostbite times:
light gray—frostbite could occur in 30 minutes;
medium gray—frostbite could occur in 10 minutes;
dark gray—frostbite could occur in 5 minutes.
From the U.S. National Weather Service.

ambient temperature more rapidly than without wind. In humans, because heat continuously moves from core to skin, wind will increase heat loss. The WCT presents the relative risk of frostbite and the predicted time to freezing of exposed facial skin walking at 1.3 m/s (3 mph) (20). Facial skin was used because this region is most often unprotected; however, vasoconstriction results in a greater decrease in blood flow to the extremities, which may increase the susceptibility of fingers and toes to freezing. Wet skin exposed to the wind will cool even faster; therefore, under wet conditions the ambient temperature used for the WCT table should be 10°C lower than the actual ambient temperature (21). Note that frostbite cannot occur if the air temperature is above 0°C (32°F).

Operational Effectiveness

Operational effectiveness, that is, the ability to perform task requirements without being debilitated by the environment, depends on (i) proper assessment of the environmental threat (air temperature, wind speed, potential for precipitation or immersion); (ii) identification of increased susceptibility (due to physiological factors such as fatigue, or individual factors, such as dehydration, body composition, fitness level or illness); (iii) implementation of controls (appropriate clothing, fluid availability, work/rest cycles, ability to cool or warm, etc.); and (iv) heat and cold injury recognition, mitigation methods, and first aid.

Heat Stress

Flight crews encounter heat stress during preflight, engine start, taxiing out, and standing by for takeoff. Total ground time can be considerable even in fighter aircraft. In addition, the heat load experienced in the cockpit is more severe than on the ramp because of the reduced air velocity, personal equipment worn, and increased radiant heat load. The WBGT index may be increased as much as 20°F (11°C) or higher in the cockpit (22). Although fighter crews experience only limited physical workloads in the cockpit, flight clothing imposes a significant thermal burden for hot weather operations. The multilayered, protective clothing includes cotton underwear, fire-retardant coveralls, antigravity suits, parachute harness, boots, gloves, and helmet. A chemical defense layer may be added as underwear or incorporated into the coverall. The process of dressing in the ensemble, walking to the aircraft, and conducting preflight inspection on a hot ramp significantly raises core temperature (22). As a result, dehydration can be a factor resulting from increased sweating due to heat exposure, encapsulation, and increased work output due to protective clothing. Furthermore, because the flight crews are dressed in multiple clothing layers, and may have to wait for long periods on the runway to be cleared for takeoff, they may not drink fluid to avoid having to urinate. Therefore, it is an already warm and possibly dehydrated crew that enters the cockpit of a heat-soaked aircraft and goes through the sequences required for engine start. Moreover, in wartime, crews are expected to fly two, three, or more missions in quick succession with little change and cannot achieve full recovery in terms of body temperature and hydration status (22).

Dehydration and Performance

Dehydration refers to a loss of total body water (TBW) resulting in a fluid deficit. Under ordinary circumstances, body water is well maintained by physiological (fluid regulatory hormones) and social/behavioral factors (23). When a body water deficit occurs, plasma volume decreases and plasma osmotic pressure increases in proportion to the decrease in TBW (23). Plasma volume decreases because it provides the fluid for sweat, and osmolality increases because sweat is hypotonic relative to plasma. These changes combine to increase cardiovascular and thermoregulatory strain by a delay in the onset of sweating, reduced skin blood flow, and stroke volume. The deleterious consequences to exercise performance are well recognized when dehydration exceeds approximately 2% of body mass (∼3% of TBW) and they are exacerbated by heat stress (23). The negative impact of dehydration on cognitive performance has also been established. Flight crews of high-performance aircraft have unique stressors that can interact with those of heat and dehydration. Specifically, aerial combat entails sequences of complex maneuvers with levels of accelerations (G-stress), which challenge human tolerance limits. Both heat stress and dehydration can lower the threshold at which the crew may lose consciousness.

Typical flying duties involve limited amounts of physical work (100–250 W) (18), but the mental workload associated with fighter missions and other flight scenarios can be substantial (23). The potential for dehydration, heat stress, or their combination to reduce cognitive function has been studied using multiple cognitive testing modalities. Interpretation of the many reports is difficult because the design of most studies does not allow distinction between the effect of thermal (or exercise) stress and that of dehydration. In one very well-designed study, Gopinathan et al. (24) determined the arithmetic ability, short-term memory, and visual-motor tracking in 11 men who, on separate days, had undergone dehydration levels of either 1%, 2%, 3%, or 4%. The subjects had ample rest in a thermoneutral environment once they reached the target level of dehydration. This allowed observation of the effects of dehydration *per se*, without fatigue or heat stress. The study revealed that, like physical performance, deterioration of mental functions occurs at a threshold level of 2% dehydration. More direct pilot performance measures like gray-out tolerance time also appear to be impaired by dehydration at high acceleration (7 G) (25), but this may not be a factor at lower levels of acceleration (3 G) (26). However, given the importance of mental function to the flight or high-performance aircraft, it is important to remember that even a small possibility of pilot error can have disastrous consequences.

Physiologic factors that contribute to dehydration-mediated cognitive and acceleration tolerance performance decrements have not been well elucidated. The relative hyperthermia associated with dehydration could diminish psychological drive (27) or perhaps alter central nervous system function independent of temperature. Cerebral blood flow is diminished in response to an orthostatic challenge by both prior heat stress and dehydration (28). This could impact cerebral oxygen availability, which itself is altered by G_z (29). It also appears that intracranial volume is altered in response to dehydration (30), although the exact functional consequence of this is unknown. It is recommended that pilots of high-performance aircraft do not become dehydrated by more than 1% of body mass (31). This would also assist in preventing body temperature from rising more than 1°C (18). When flying multiple sorties, proper postflight hydration practices (18) should foster a normal level of hydration. Drinking fluids until the flight briefing period will provide ample time for the bladder to empty before preflight and flight phases of the next sortie. Another approach is to mitigate heat strain in the taxi and flight phases to minimize dehydration through sweat losses. The interaction of dehydration and heat stress on $+G_z$ tolerance and cognitive functions are additive (23,31); therefore, active pilot cooling in a hot cockpit is essential.

Mitigation

Low-level flights in hot climates can produce environmental heat stress that exceeds FITS caution and danger limits (18). Modern fighter aircraft often have cockpit cooling during ground operations (standby and taxi). However, if protective clothing must also be worn the occupants receive limited benefit from in-cockpit cooling, and the added insulation and vapor resistance can impose additional heat stress and compromise thermoregulation and cognitive performance (32,33). In addition, cockpit cooling is limited, and typically, heat removal occurs so slowly that the aircraft is in combat or returning to base before cooling is complete. Microclimate cooling systems are an effective means of mitigating cockpit thermal heat stress.

Microclimate cooling systems remove body heat by conduction (ice), convection and conduction (perfused water), or convection and evaporation (compressed or conditioned air). Under ideal conditions for a given category of cooling system, the most popular form of cooling garment for the aviator (vest) can remove well above 100 W of body heat (34). Head cooling has also been tried and may improve thermal comfort (35), but by itself removes much less heat (25,35) and can produce headache if overcooled (36). In some flight circumstances, the use of microclimate heating—particularly heating of the extremities (warmed gloves and boots)—may be desirable, but the principle concern for the aviator is management of heat stress.

Figure 7-7 (34) depicts a modeling simulation (37) for the relationship between endurance time (minute) and cooling extraction rate (W) over a broad range of metabolic rates when wearing protective clothing in a hot, dry environment. At realistic metabolic rates for aviators (100–250 W) (18), work times without cooling improve from approximately 70 minutes to more than 300 minutes with the application of 100–150 W of microclimate cooling. All three categories of microclimate cooling systems will reduce heat stress and strain in a hot cockpit and improve performance whether worn beneath ordinary or protective clothing ensembles (38,39).

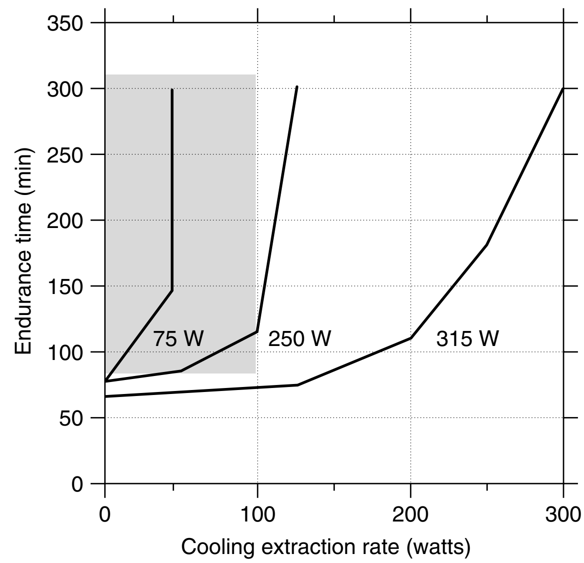


FIGURE 7-7 Modeling simulation of the relationship between endurance time and cooling extraction rate at various metabolic rates (75 and 315 W) in a hot, dry environment when donning protective clothing. Gray zone signifies improvement in endurance time from approximately 70 minutes to greater than 300 minutes with the application of 100 W of microclimate cooling at a metabolic rate consistent with the demands of aviation. (Modified from Pandolf KB, Gonzalez RR, Sawka MN, et al. *Tri-service perspectives on microclimate cooling of protective clothing in the heat*, Technical Report No.: T95–10, USAMRMC, 1995.)

Heat Acclimatization

Biological adaptations to repeated heat stress include heat acclimatization and acquired thermal tolerance, defined as adaptations that provide greater resistance to heat injury. The magnitude of both adaptations depends on the intensity, duration, frequency, and number of heat exposures. These adaptations are complementary as heat acclimatization reduces physiologic strain, and acquired thermal tolerance improves tissue resistance injury to a given heat strain. Heat acclimatization is induced when repeated heat exposures are sufficiently stressful to elevate core and skin temperatures and elicit profuse sweating. During initial heat exposure, physiologic strain will decrease each subsequent day of heat acclimatization. These adaptations include earlier onset of sweating and greater sweat volumes, better fluid balance, improved cardiovascular stability, and lowered metabolic rate. Overall, acclimatization will result in reductions in core temperature and perception of effort while performing physical work in the heat. The most important physiologic adaptation is improved sweating because earlier sweating and greater sweat volumes increase heat loss and lower cardiovascular strain. However, the use of protective clothing may hamper the evaporation of this greater sweating response.

Heat acclimatization is specific to the climate and activity level; therefore, if personnel will be working in a hot, humid climate, heat acclimatization should be conducted under similar conditions. Typically, approximately 2 weeks of progressive heat exposure and physical work should be allowed for heat acclimatization, with daily durations of at least 100 minutes. Individuals who are less fit or unusually susceptible to heat will require several days or weeks more to acclimatize. Highly fit individuals can achieve heat acclimatization in approximately 1 week. In addition, several weeks of living and working in the heat (seasoning) may be required to maximize tolerance to high body temperatures. Adequate water must be provided and consumption monitored during and after the acclimatization period. Heat acclimatization increases the sweating rate, and therefore increases water requirements. Heat acclimatization will be retained by approximately 1 week if heat exposure no longer occurs and 75% of the adaptation is lost by approximately 3 weeks (10).

Cold Stress

Cold stress is known to adversely affect both cognitive and physical performance. Physical performance tasks are more directly related to tissue cooling, which impairs muscle strength, slows nerve conduction velocity, and reduces joint mobility. Although local tissue cooling may initially degrade manual performance at skin temperatures as high as 20°C, an abrupt performance degradation occurs when skin temperature falls below 15°C (40), and another subsequent drop occurs at approximately 4°C as tactile sensitivity is impaired. A decreased core temperature is associated with degradation of cognitive and psychomotor tasks (41).

Although much data exist, it remains difficult to predict performance degradation in cold environments. Under some conditions, both cognitive and physical performance may be maintained during cold exposure, even with moderate decreases in core temperature. While it is suggested that the cold environment causes distraction, resulting in inattentiveness to the task at hand, Enander (42) suggests that arousal due to mild cold exposure could account for improved performance that sometimes occurs. Whether performance is degraded or even enhanced during cold exposure may be related to how the individual manages the pressure to perform and/or anxiety associated with the cold stress. It follows then that degradation in performance could be limited by training under stressful scenarios such as cold stress and while wearing cold-weather clothing, once the task has been learned under ideal conditions, to ensure optimal skill development. This strategy has been found to be effective for improving manual dexterity in cold environments that could prove useful for ground crews working outdoors.

In cold environments, humans rely heavily on "behavioral thermoregulation," which includes use of shelter, clothing, and physical activity to maintain body temperature. The most effective protection of course would be to go inside an enclosed, insulated, heated building. However, working in a climate-controlled hangar may not be available for many ground and flight crews. Different types of cold stress present different challenges for management. For example, during cold air exposure (10°C), individuals dressed only in shorts and socks can maintain their core temperature for more than 4 hours (43), whereas at the same temperature (10°C) the chest-deep cold water immersion causes a 1°C fall in core temperature within 90 minutes. During cold air exposure, the primary concern may be localized cold injury to exposed skin (e.g., frostbite at temperatures below freezing) or reduced manual dexterity due to extremity cooling (42), whereas during cold water immersion, the primary concern is hypothermia induced by rapid heat loss. The effective countermeasures in each of these scenarios may also differ. While exercise is effective for increasing extremity blood flow during cold air exposure, thereby improving thermal comfort and physical function and reducing risk of peripheral cold injury, exercise during cold water exposure less than 18°C is likely to increase the rate of heat loss and exacerbate core cooling.

Clothing—Creating a Microenvironment

The insulation value of clothing is primarily related to how much air is trapped between the fibers, as air is an excellent insulator. Table 7-3 presents clothing insulation values of typical uniforms. Air can also be trapped between layers of clothing and therefore increase insulation. An example of this can be seen in Table 7-4, where the addition of the nylon jacket and pants to the physical training uniform more than doubles the insulation, although nylon has little insulation value itself; the loose fit and wind-resistant property of the fabric increases the trapped air between the layers of clothing. On the other hand, the total insulation of a cold weather system is less than the sum of the garments that are worn because each layer actually adds some compression to

TABLE 7-3

Insulation Value of Different Pieces of U.S. Army and Air Force Clothing

Item	*Insulation value (clo)*
Improved physical fitness uniform	0.30
Improved physical fitness uniform + nylon jacket and pants	0.70
U.S. Air Force Nomex flight suit	1.15
Aviation fuel handler's protective coverall	1.25
U.S. Army desert battle dress uniform	1.32
U.S. Air Force Nomex flight suit + chemical protective undergarment	1.72
Gore-Tex parka and trousers	1.95
Fleece jacket, bib overall	2.37

TABLE 7-4

Time in Seconds to Reach a Finger-Skin Temperature of 32°F while Touching Various Materials at Different Temperatures

Material Temperature (°F)	*Aluminum (Seconds)*	*Steel (Seconds)*	*Stone (Seconds)*
32	43	>100	>100
23	15	50	>100
14	5	15	62
5	2	5	20
−4	1	2	7
−13	<1	<1	4

the layer underneath. The addition of chemical protective garments will not only increase overall insulation but can also limit evaporation of sweat if individuals are partially or fully encapsulated. The decision of what to wear is not necessarily straightforward and likely differs among individuals and may be dictated by conditions or mission tasks. Practice, particularly under varied environmental conditions, activity levels, and tasks, is critical for learning how best to use clothing to maintain comfort and performance.

In the extremities, blood flow is greatly reduced during cold stress, and there is little local metabolic heat production. Finger cooling can be exacerbated by touching cold objects, which is important for ground crews working outdoors. In a cold environment, touching tools, equipment, or the aircraft itself could result in a freezing tissue injury. Table 7-4 presents the time for finger skin to cool to freezing as bare skin contacts different materials. The high conductivity of aluminum is again apparent, with comparatively lower conductivity for steel and stone (Table 7-5). It illustrates the importance of anticontact gloves whenever the temperature falls below freezing. Ground crews should be aware that special precautions are required for handling fuel or petroleum products that remain liquid even at temperatures of −40°C or below. Contact of bare skin with these fuels can cause instantaneous frostbite; therefore, protective gloves are mandatory (Figure 7-8).

TABLE 7-5

Conductivity of Various Materials

Material	*Conductivity K (W/m·K)*
Air	0.024
Wood	0.1
Snow	0.1-0.3
Asphalt	0.2-0.5
Water	0.6
Concrete	0.8
Ice	1.6
Granite	2.2
Steel	50
Aluminum	205

FIGURE 7-8 Ground crew performing maintenance can lose heat through conduction to tarmac or flight deck, or through contact with hand tools or contact with the aircraft itself.

Thermal Stress and Microgravity

One particular challenge to thermoregulation during spaceflight is the restriction of conductive and evaporative cooling due to the design of the space suits worn. The development of protective garments such as the launch entry suit (LES) and advanced crew escape suit (ACES) were designed to provide protection against external element changes such as high cabin temperatures, cold water immersion, pressure changes, and any ambient gas changes (44). However, the microenvironments that these suits create by storing heat can also be detrimental. Despite new technology, the suits that are worn are bulky and difficult to move. Because all objects have mass, even in zero gravity, energy is required for movement, thereby increasing body temperature. A rise in the energy cost of ambulation, in addition to restricted evaporation due to encapsulation, increases the risk of hyperthermia.

The LES was the original garment worn by the astronauts and consisted of polypropylene underwear, an antigravity suit, a double-layer nylon exterior, and a helmet (45). While the suit prevents body heat losses in the event of water immersion, the LES also retained heat, detrimental in the hot cabin atmosphere, as it did not allow for evaporative or conductive cooling and resulted in increased core body temperatures. To aid in conductive thermoregulation, liquid cooling garments (LCGs) were developed that pass cool water through tubes lying against the skin, promoting heat loss from the skin through conduction. The outer layer of the newer ACES consists of a Gore-Tex shell, which theoretically allows the heat that is produced by the body to be released to the environment more readily than in previous suits (44).

An additional means of reducing the risk of hyperthermia in a zero gravity environment is maintenance of normal fluid balance. One exacerbating factor in maintaining fluid balance is a phenomenon that occurs in zero gravity where there is an acute upward shift of blood volume. This upward shift in blood volume stimulates central volume receptors and triggers hormones of fluid regulation, resulting in an increase in diuresis, negative fluid balance, and hypovolemia (46), effectively reducing thermoregulatory sweating. A hydration plan that helps to maintain normal fluid balance by increasing fluid intake before or during space flight might preserve thermoregulatory sweating. In a microgravity environment, with suits that allow for evaporation, this sweat would spread across the surface of the skin, effectively creating a large, wet surface, increasing evaporative cooling, and reducing risk of hyperthermia.

Exercise

By increasing body heat content, exercise is effective at elevating extremity temperatures, as well as core temperature, even in hypothermic individuals. Moderate exercise (e.g., walking at 3.5 mph) can be effective for maintaining finger temperatures during cold air exposure as low as −22°F when appropriate cold-weather clothing is worn. Clothing insulation must typically be reduced during exercise to avoid sweating because damp clothing has a lower insulation value and will increase conductive heat loss when exercise stops. Figure 7-9 presents the clothing insulation (clo) required over a range of cold conditions as metabolic rate increases due to activity.

Water Immersion

The conductivity of water is 25 times that of air, and hypothermia can be a concern even in water temperature as high as 70°F to 75°F. Risk of hypothermia depends on water temperature, immersion depth, and immersion duration. Exercise can increase heat loss as blood flow to extremities and working muscles increases; therefore, swimming to shore should only be attempted if the individual is confident of reaching land. Otherwise, heat conservation is the best strategy and is most effective by maintaining a posture that minimizes both the surface area in contact with the water and the movement, such as the H.E.L.P. position (Figure. 7-10). Immersion suits are designed to provide both floatation

FIGURE 7-10 H.E.L.P. position.

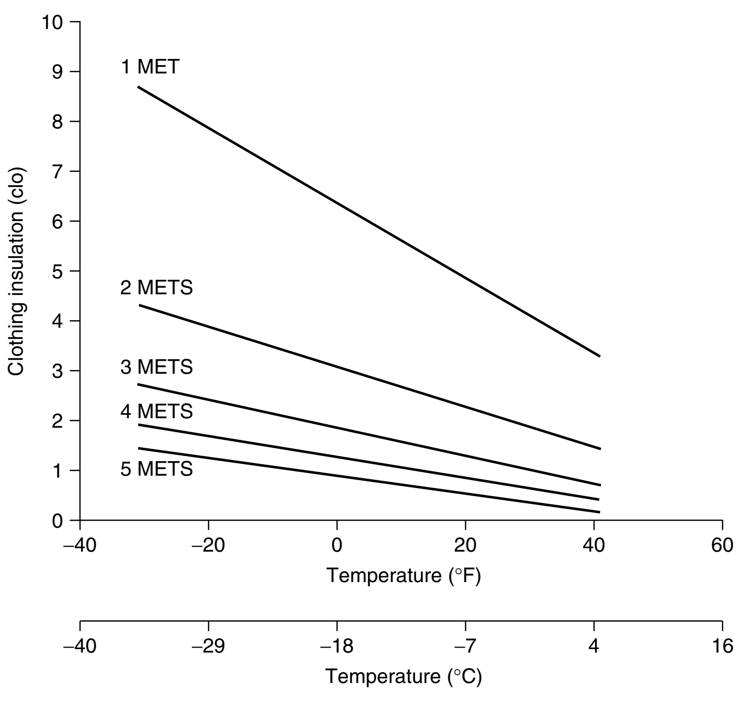


FIGURE 7-9 Interaction of clothing insulation (clo), environmental temperature (°F, °C), and exercise intensity (METS). The less the insulation factor of clothing, the greater the exercise intensity (metabolic heat production) required to maintain normal body temperature. The greater the insulation of clothing, the less metabolic heat production required.

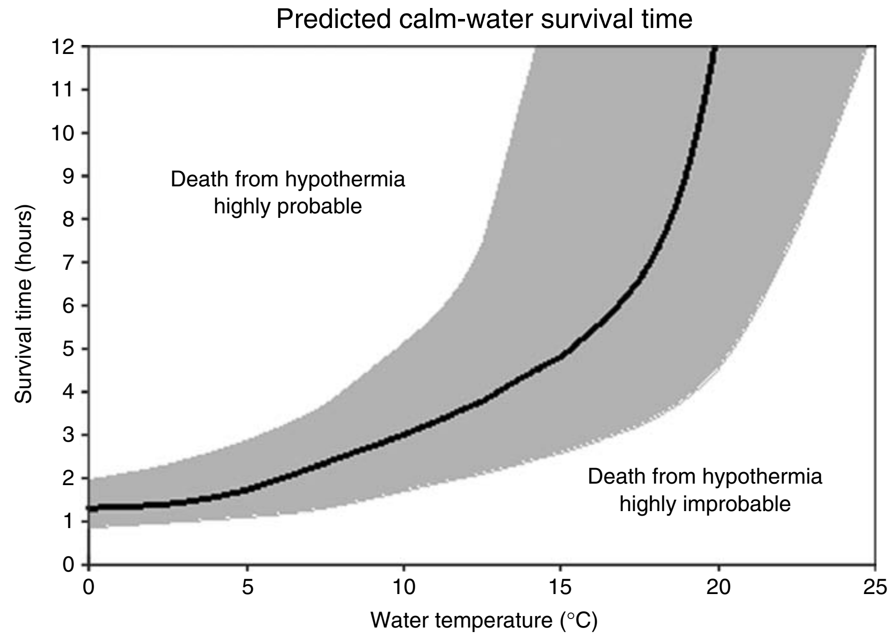


FIGURE 7-11 Average survival time in different water temperatures. Individuals who lose heat quickly (gray area below the line) will have significantly less time to survive versus individuals who cool at a slow to average rate (gray area above the line).

and insulation and can dramatically extend functional time in cold water. Recent research has demonstrated that motion sickness may increase the risk of hypothermia during cold water immersion by blunting both shivering and vasoconstrictor responses (47). Figure 7-11 shows the average survival time in different water temperatures. In calm water, at temperatures approaching approximately 20°C, survival rate increases dramatically. Individuals who lose heat quickly (gray area below the line) will have significantly less time to survive compared to individuals who cool at a slow to average rate (gray area above the line). For additional information about cold water survival, see the suggested readings for a cold water rescue attempt of a U.S. navy patrol aircraft.

Environmental Injury and Illness

Heat Illness and Injury

Minor heat illnesses include heat rash, heat cramps, and heat syncope, whereas serious heat illnesses include heat exhaustion, heat injury, and heat stroke. Factors that increase risk of serious heat illness or injury include lack of heat acclimatization, low physical fitness, dehydration, and high body fat/mass, and certain medications. However, serious heat illness can occur in low-risk persons who are practicing sound heat mitigation procedures.

Wearing encapsulated, protective clothing such as G-suits for prolonged periods can cause heat rash or prickly heat due to hygiene issues. Heat rash can interfere with heat exchange across the skin, thereby increasing the risk of heat exhaustion and heat stroke. Heat cramps are muscle pains or spasms in the abdomen, arms, or legs that may occur in association with strenuous activity. Heat cramps usually affect people who sweat profusely, typically during strenuous activity, and lose an appreciable amount of electrolytes, mainly sodium chloride, in their sweat. Heat syncope is a temporary circulatory failure due to the pooling of blood in the peripheral veins, particularly those of the lower extremity, resulting in a decrease in diastolic filling of the heart. Symptoms range from lightheadedness to loss of consciousness. Heat syncope typically occurs during prolonged standing in hot environments but can also occur if standing still after completing vigorous activity. Individuals suffering from heat syncope will recover rapidly once they sit or lie supine; however, complete recovery of stable blood pressure and heart rate may take a few hours.

Heat exhaustion is the most common form of serious heat illness. It occurs when the body cannot sustain the level of cardiac output needed to support skin blood flow for thermoregulation and blood flow for metabolic requirements of exercise. Signs and symptoms of heat exhaustion include syncope, headache, nausea, vomiting, loss of appetite, hypotension, tachycardia, muscle cramps, hyperventilation, and transient alteration in mental status.

Heat stroke is characterized by elevated body temperature (>40°C or 104°F) and profound central nervous system dysfunction that results in delirium, convulsions, or coma. Heat stroke is a catastrophic medical emergency that can result in multiorgan dysfunction. The onset of heat stroke may be preceded by headache, dizziness, drowsiness, restlessness, ataxia, confusion, and irrational or aggressive behavior, or may occur suddenly with symptoms of convulsions, delirium, vomiting, and unconsciousness. The skin may be hot and dry but can still be moist from sweat. Those suffering from heat stroke should be immediately taken to an emergency medical treatment facility. The most important treatment is rapid reduction of body core temperature. Cooling should begin in the field, where individuals are moved to a cool, shady place, clothes removed, and skin kept moist. The victim should be immersed in cool/cold water if possible, while waiting for transport. If not possible, spraying with cold water, and fanning while waiting for transport and/or during transport, can be effective in lowering body core temperature. For both heat exhaustion and heat stroke, active cooling should continue until the rectal temperature is less than 101°F (38.3°C) at which time cooling should stop to prevent hypothermia.

Cold Injury

Cold injuries are almost always preventable. Vigilance is required for early detection so that prompt treatment is effective. Cold injury can be life threatening, as in the case of hypothermia, or cause lifelong debilitation, as in the case of frostbite. Severe frostbite could require amputation of affected tissue.

Hypothermia is defined clinically as the core temperature below 35°C, at which point most individuals will have maximal shivering. Early signs of hypothermia include slurred speech and loss of coordination, and may be mistaken for intoxication. As hypothermia progresses, shivering increases and body temperature will fall rapidly; therefore, the time to begin rewarming is when the individual is vigorously shivering and able to still generate heat. Wet clothing must be removed because it greatly increases heat loss. Insulation and protection from wind is critical if rewarming in the field. If the individual is shivering, adding insulation and limiting further heat loss will allow shivering to be effective for rewarming. However, if shivering has ceased, external heat will have to be provided. Both pulse and respiratory rates may be difficult to detect in hypothermic patients because they are slow and shallow. Cardiopulmonary resuscitation (CPR) should only be initiated if these life signs are truly absent because heart arrhythmias can be initiated by the CPR procedure itself. Use of alcohol to "rewarm" an individual is contraindicated. Alcohol interferes with hepatic glucose production and causes hypoglycemia, which blunts the shivering response and causes vasodilation of skin blood vessels resulting in greater heat loss from the skin to the environment.

Peripheral Cold Injuries

Peripheral cold injuries can be divided into two categories: freezing (i.e., frostbite) and nonfreezing (trench foot and chilblain). The freezing point of skin is slightly below the freezing point of water due to the electrolyte content of the cells and extracellular fluid, with the skin surface reportedly freezing from −3.7°C to −4.8°C (48). Both wetness and wind will increase the rate of cooling. Frostbite is most common not only in exposed skin (nose, ears, cheeks, and exposed wrists) but also occurs on the hands and feet because peripheral vasoconstriction significantly lowers tissue temperatures (49). The wind chill equivalent temperature chart (Table 7-2) indicates the risk of bare skin freezing during exposure to different combinations of air temperature and wind speed, with guidance on how long it will take for skin to freeze under those conditions. The risk is greatly reduced by covering skin with appropriate clothing, and by monitoring signs and symptoms of frostbite. Individuals often report feeling a "wooden" sensation in the injured area. After rewarming, pain is significant. The initial sensations are an uncomfortable sense of cold, which may include tingling, burning, aching, sharp pain, and decreased sensation (50). The skin color may initially appear red and later it becomes waxy white. Buddy checks are important for prevention of frostbite because the loss of sensation often means that the injury is not perceived by the patient. Rapid rewarming (ideally in a warm water bath at 40°C) will minimize tissue damage; however, in field environments rewarming should not be attempted unless refreezing of the injury can be avoided because refreezing would damage tissues more than delayed rewarming. As mentioned previously, contact frostbite can occur rapidly at very cold temperature, and can occur in seconds in contact with metal objects and with petroleum fuels, oils, and lubricants having freezing points below −40°C.

Nonfreezing Cold Injuries

Nonfreezing injuries can occur at temperatures above freezing, particularly when skin or clothing is damp. Trench foot earned its name after its prevalence during World War I when soldiers were confined to sedentary positions with wet feet, either due to standing in water or simply from sweat-soaked socks. Trench foot typically occurs when tissues are exposed to temperatures between 0°C and 15°C (32°F–60°F) for prolonged periods of time (50), whereas chilblains, a more superficial injury, can occur after just a few hours of exposure to bare skin (50). Diagnosing nonfreezing cold injuries involves observation of clinical symptoms over time as different and distinct stages emerge days to months after the initial injury (51). Prevention requires frequent changing of socks to ensure that feet stay clean and dry. Physical movement is also important to maintain blood flow to the feet. If injury occurs, recovery can be prolonged. Chilblain produces swollen, tender, itchy, and painful skin that may continue for several hours after rewarming, but has no lasting effects.

Other medical issues related to cold exposure include cold-induced bronchospasm (CIB) or asthma, cold urticaria, and snow blindness. CIB can occur upon exposure to cold, dry air even in individuals who do not normally have exercise-induced asthma, and affects approximately 25% of elite winter athletes (51). This is attributed primarily to facial cooling rather than breathing cold air (52); however, while limiting facial cooling (e.g., by wearing a balaclava) could decrease the degree or incidence of CIB, some subjects may still experience symptoms. To minimize airway cooling, heat and moisture exchange (HEM) modules have been developed that are intended to help warm and humidify inspired air. Although these devices are of little value for reducing respiratory heat or moisture loss during cold exposure, they do have value for limiting cold-induced asthma (CIA) or CIB (53). Cold urticaria is probably the most common form of urticaria and is characterized by the rapid onset of itching, redness, and swelling of the skin (hives) within minutes of exposure to a cold stimulus (54). In extreme cases, anaphylactic shock may occur. Another concern is the glare of the sun on white snow that can cause snow blindness due to the reflective glare. This malady can be prevented with protective eyewear. Extensive treatment on the care and prevention of thermal illnesses and injury can be found in TB MED 507 and TB MED 508 (22,55).

Monitoring Body Temperature

In a situation of heat or cold illness or injury, measurement of core temperature is important to determine the extent of the change in body core temperature and to establish a course of treatment. Monitoring internal body core temperature (Tc) accurately requires invasive methodologies. The mercury thermometer is commonly used to measure oral temperature. Other Tc sites such as rectal and esophageal temperatures are commonly measured; esophageal temperature is performed more typically in research settings. Measurement of Tc at these as well as other sites may not be practical in the field. However, Tc measured at sites such as the axillary region, tympanic membrane, and body surface using other measurement devices may be more convenient but may not accurately assess true Tc. For example, oral and tympanic membrane temperatures are generally unreliable in cold environments; therefore, rectal temperature is generally used. Esophageal temperature is a better representation of central blood temperature and more responsive under changing conditions, but is difficult to obtain due to the invasiveness of the technique and the discomfort of the individual. Telemetric temperature pills can be a good alternative for ambulatory field conditions, but are expensive, require a data logging device, and would not be feasible for giving a patient orally upon suspecting hyper- or hypothermia. However, telemetric pills may be used as a suppository with individuals who are either unresponsive or may be convulsing, where use of a glass rectal thermometer may be dangerous. In the event that a patient has diarrhea, a flexible rectal thermistor may be better option. Overall, rectal temperature remains the most accurately available method for monitoring Tc during thermal illness.

ACKNOWLEDGMENTS

The authors wish to thank Ms. Brett Ely, Mr. Daniel Goodman, Ms. Laura Palumbo, and Mr. Thomas Endrusick for their assistance and Dr. Michael Sawka for editorial oversight.

The views, opinions, and/or findings in this report are those of the authors and should not be construed as official Department of the Army position, policy, or decision unless so designated by other official designation. All experiments were carried out in accordance to state and federal guidelines.

REFERENCES

1. Gagge AP, Gonzalez RR. Mechanisms of heat exchange: biophysics and physiology. In: Fregly MJ, Blatteis CM, eds. *Handbook of physiology: environmental physiology*. Bethesda: American Physiological Society, 1996:45–84.
2. Sawka MN, Young AJ. Physiological systems and their responses to conditions of heat and cold. In: Tipton CM, ed. *ACSM's advanced exercise physiology*. Philadelphia: Lippincott Williams & Wilkins, 2006:535–563.
3. Shibasaki M, Kondo N, Crandall CG. Non-thermoregulatory modulation of sweating in humans. *Exerc Sport Sci Rev* 2003;31:34–39.
4. Stephenson LA, Kolka MA. Menstrual cycle phase and time of day alter reference signal controlling arm blood flow and sweating. *Am J Physiol* 1985;249:R186–R191.
5. Roberts MF, Wenger CB, Stolwijk JAJ, et al. Skin blood flow and sweating changes following exercise training and heat acclimation. *J Appl Physiol* 1977;43:133–137.
6. Toner MM, McArdle WD. Human thermoregulatory responses to acute cold stress with special reference to water immersion. In: Fregley MJ, Blatteis CM, eds. *Handbook of physiology: environmental physiology*. Bethesda: American Physiological Society, 1996:379–418.
7. Stocks JM, Taylor NA, Tipton MJ, et al. Human physiological responses to cold exposure. *Aviat Space Environ Med* 2004;75:444–457.
8. Bell DG, Tikuisis P, Jacobs I. Relative intensity of muscular contraction during shivering. *J Appl Physiol* 1992;72:2336–2342.
9. Eyolfson DA, Tikuisis P, Xu X, et al. Measurement and prediction of peak shivering intensity in humans. *Eur J Appl Physiol* 2001;84:100–106.
10. Sawka MN, Young AJ. Physical exercise in hot and cold climates. In: Garrett WE, Kirkendall DT, eds. *Exercise and sport science*. Philadelphia: Lippincott Williams & Wilkins, 2000:385–400.
11. O'Brien C, Young AJ, Sawka MN. Hypohydration and thermoregulation in cold air. *Eur J Appl Physiol* 1998;84:185–189.
12. Castellani JW, Young AJ, Ducharme MB, et al. Prevention of cold injuries during exercise. *Med Sci Sports Exerc* 2006;38:2012–2029.
13. Daanen HAM. Finger cold-induced vasodilation. *Eur J Appl Physiol* 2003;89:411–426.
14. Yaglou CP, Minard D. Control of heat casualties at military training centers. *AMA Arch Ind Health* 1957;16:302–316.
15. Haldane JS. The influence of high air temperatures. *J Hyg (Lond)* 1905;5:494–513.
16. Cadarette BS, Matthew WT, Sawka MN. *WBGT index temperature adjustments for work/rest cycles when wearing NBC protective clothing or body armor*. USARIEM Technical Report No.: TN05-04 (AD ADA435964). 2005.
17. Harrison MH, Higenbottam C, Rigby RA. Relationships between ambient cockpit and pilot temperatures during routine air operations. *Aviat Space Environ Med* 1978;49:5–13.
18. Nunneley SA, Stribley RF. Fighter index of thermal stress (FITS): guidance for hot-weather aircraft operations. *Aviat Space Environ Med* 1979;50:639–642.
19. National Weather Service. *Windchill temperature index*, 2001.
20. Ducharme MB, Brajkovic D. *Guidelines on the risk and time to frostbite during exposure to cold wind, Proceedings of the RTO NATO Factors and Medicine Panel Specialist Meeting on Prevention of Cold Injuries*. 2–1–2–9, 2005.
21. Brajkovic D, Ducharme MB. Facial cold-induced vasodilatation and skin temperature during exposure to cold wind. *Eur J Appl Physiol* 2006;96:711–721.
22. Departments of the Army and Air Force. *Heat stress control and heat casualty management. Technical Bulletin Medical 507/Air Force Pamphlet 48–152(I)*, 2003.
23. Institute of Medicine. *Dietary reference intakes for water, potassium, sodium, chloride, and sulfate*, 2005.

24. Gopinathan PM, Pichan G, Sharma VM. Role of dehydration in heat stress-induced variations in mental performance. *Arch Environ Health* 1988;43:15–17.
25. Nunneley SA, Reader DC, Maldonado RJ. Head-temperature effects on physiology, comfort, and performance during hyperthermia. *Aviat Space Environ Med* 1982;53:623–628.
26. Greenleaf JE, Matter M, Bosco JS, et al. Effects of hypohydration on work performance and tolerance to $+G_z$ acceleration in man. *Aerosp Med* 1966;37:34–39.
27. Bruck K, Olschewski H. Body temperature related factors diminishing the drive to exercise. *Can J Physiol Pharmacol* 1987;65:1274–1280.
28. Carter R III, Cheuvront SN, Vernieuw CR, et al. Hypohydration and prior heat stress exacerbates decreases in cerebral blood flow velocity during standing. *J Appl Physiol* 2006;101:1744–1750.
29. Kobayashi A, Tong A, Kikukawa A. Pilot cerebral oxygen status during air-to-air combat maneuvering. *Aviat Space Environ Med* 1979;50:639–642.
30. Dickson JM, Weavers HM, Mitchell N, et al. The effects of dehydration on brain volume—preliminary results. *Int J Sports Med* 2005;26:481–485.
31. Nunneley SA, Stribley RF. Heat and acute dehydration effects on acceleration response in man. *J Appl Physiol* 1979;47: 197–200.
32. Ferevik H, Reinertsen RE. Effects of wearing aircrew protective clothing on physiological and cognitive responses under various ambient conditions. *Ergonomics* 2003;46:780–799.
33. Reardon M, Fraser B, Omer J. Physiological effects of thermal stress on aviators flying a UH-60 helicopter simulator. *Mil Med* 1998;163:298–303.
34. Pandolf KB, Gonzalez RR, Sawka MN, et al. *Tri-service perspectives on microclimate cooling of protective clothing in the heat*, Technical Report No.:T95–10. USAMRMC, 1995.
35. Nunneley SA, Maldonado RJ. Head and/or torso cooling during simulated cockpit heat stress. *Aviat Space Environ Med* 1983;54: 496–499.
36. Cadarette BS, DeCristofano BS, Speckman KN, and Sawka MN. Evaluation of three microclimate cooling systems. *Aviat Space Environ Med* 61:71–76, 1990.
37. Pandolf KB, Stroschein LA, Drolet LL, et al. Prediction modeling of physiological responses and human performance in the heat. *Comput Biol Med* 1986;16:319–329.
38. Banta GR, Braun DE. Heat strain during at-sea helicopter operations and the effect of passive microclimate cooling. *Aviat Space Environ Med* 1992;63:881–885.
39. Vallerand AL, Michas RD, Frim J, et al. Heat balance of subjects wearing protective clothing with a liquid- or air-cooled vest. *Aviat Space Environ Med* 1991;62:383–391.
40. Heus R, Daanen HAM, Havenith G. Physiological criteria for functioning of hands in the cold. *Appl Ergon* 1995;26:5–13.
41. O'Brien C, Mahoney C, Tharion WJ, et al. Dietary tyrosine benefits cognitive and psychomotor performance during body cooling. *Physiol Behav* 2007. Feb 28;90(2–3):301–7.
42. Enander A. Effects of moderate cold on performance of psychomotor and cognitive tasks. *Ergonomics* 1987;30:1431–1445.
43. Young AJ, Castellani JW, O'Brien C, et al. Exertional fatigue, sleep loss, and negative energy balance increase susceptibility to hypothermia. *J Appl Physiol* 1998;85:1210–1217.
44. Lee SMC, McDaniel A, Jacobs T, et al. *Performance of the liquid-cooling garment with the advanced crew escape suit in elevated cabin temperatures*, 2004. NASA/TP-2004-212074.
45. Bagian JP, Kaufman JW. Effectiveness of the Space Shuttle anti-exposure system in a cold water environment. *Aviat Space Environ Med* 1990;61:753–757.
46. Watenpaugh DE, Smith ML. Human cardiovascular acclimation to microgravity 20. *J Gravit Physiol* 1998;5:15–18.
47. Nobel G, Eiken O, Tribukait A, et al. Motion sickness increases the risk of accidental hypothermia. *Eur J Appl Physiol* 2006;98:48–55.
48. Danielsson U. Windchill and the risk of tissue freezing. *J Appl Physiol* 1996;81:2666–2673.
49. DeGroot DW, Castellani JW, Williams JO, et al. Epidemiology of U.S. Army cold weather injuries, 1980–1999. *Aviat Space Environ Med* 2003;74:564–570.
50. Mills WJ. Clinical aspects of freezing cold injury. In: Pandolf KB, Burr RE, eds. *Textbooks of military medicine: medical aspects of harsh environments*, Vol. 1. Falls Church: Office of the Surgeon General, U.S. Army, 2002:429–466.
51. Wilber RL, Rundell KW, Szmedra L, et al. Incidence of exercise-induced bronchospasm in Olympic winter sport athletes. *Med Sci Sports Exerc* 2000;32:732–737.
52. Koskela H, Tukiainen H. Facial cooling, but not nasal breathing of cold air, induces bronchoconstriction: a study in asthmatic and healthy subjects. *Eur Respir J* 1995;8:2088–2093.
53. Carnevale N, Ducharme MB. *Benefits of respiratory heat and moisture exchangers during cold exposures*, 1999.
54. Hamlet MP. Nonfreezing cold injuries. In: Auerbach PS, ed. *Textbook of wilderness medicine*. St. Louis: Mosby, 2001:129–134.
55. Department of the Army. Prevention and management of cold-weather injuries. *Tech Bull Med* 508, 2005.

SUGGESTED READING

Jampoler Andrew CA. *Cold water survival: 'Controlled' ditch into cold waters, the rescue of Alfa Foxtrot 586*. Naval Institute Press, Annapolis, Maryland, ISBN: 1 59114 4124, 2003.

CHAPTER 8

Cosmic Radiation

Michael Bagshaw and Francis A. Cucinotta

Cosmic rays were discovered in 1911 by the Austrian physicist, Victor Hess. The planet Earth is continuously bathed in high-energy galactic cosmic ionizing radiation (GCR), emanating from outside the solar system, and sporadically exposed to bursts of energetic particles from the sun referred to as *solar particle events* (SPEs). The main source of GCR is believed to be supernovae (exploding stars), although occasionally a disturbance in the sun's atmosphere (solar flare or coronal mass ejection) leads to a surge of radiation particles with sufficient energy to penetrate the Earth's magnetic field and enter the atmosphere. Inhabitants of planet Earth gain protection from the effects of cosmic radiation from the Earth's magnetic field and the atmosphere, as well as from the sun's magnetic field and solar wind. These protective effects extend to the occupants of aircraft flying within the Earth's atmosphere, although the effects can be complex for aircraft flying at high altitudes and high latitudes.

Travelers in space do not have the benefit of this protection and are exposed to an ionizing radiation field very different in magnitude and quality from the exposure of individuals flying in commercial airliners. The higher amounts and distinct types of radiation qualities in space lead to a large need for understanding the biological effects of space radiation. It is recognized that although there are many overlaps between the aviation and the space environments, there are large differences in radiation dosimetry, risks and protection for airline crewmembers, passengers, and astronauts. These differences affect the application of radiation protection principles of risk justification, limitation, and the principle of as low as reasonably achievable (ALARA). This chapter accordingly is divided into three major sections, the first dealing with the basic physics and health risks, the second with the commercial airline experience, and the third with the aspects of cosmic radiation appertaining to space travel including future considerations.

FUNDAMENTAL PHYSICS OF COSMIC RADIATION

Ionizing Radiation

Ionizing radiation refers to subatomic particles that, on interacting with an atom, can directly or indirectly cause the atom to lose an electron or break apart its nucleus. It is when these events occur in tissues of the body that health effects may result if the human body's self-repair mechanisms fail. Ionizing radiation types and their properties are shown in Table 8-1.

Outside the Earth's atmosphere, GCR consists mostly of fast-moving protons (hydrogen nuclei), α-particles (helium particles), and high charge and energy (HZE) nuclei ranging from lithium to uranium. GCR is 98% atomic nuclei and 2% electrons (1). Of the energetic nuclei, 87% are protons, 12% are helium ions, and 1% are heavier ions. The energy of GCR is expressed as megaelectron volt per atomic mass unit (1 mMeV/u $= 9.64853336 \times 10^{13}$ m^2/s^2). The energies range from a few MeV/u to more than 10,000 MeV/u peaking near 1,000 MeV/u. The higher energy ions move close to the speed of light.

As charged particles pass through shielding or the atmosphere and tissue, they lose energy and undergo nuclear interactions. Energy loss is caused by electromagnetic interactions transferring energy to electrons leading to ionization and excitation. The rate of energy loss increases rapidly with increasing charge of the particle and decreasing speed (2). The distance traveled depends on the energy, and massive particles are more penetrating than lighter particles of the same charge and speed. Uncharged particles have longer free paths and, for neutrons, larger energy transfers per event result in energy losses that appear as isolated occurrences along the particle's path.

Nuclear interactions produce lower charge and mass nuclei from a primary GCR nucleus and secondary radiation from the material being hit (3). The mean free path for nuclear collision is on the order of 10 cm and after

TABLE 8-1

Ionizing Radiation Types and Properties

Radiation Type	*Consists of*	*Range in Air*	*Range in Human Tissue*	*Hazard Site*[a]
β Particles	An electron	Several meters	Few millimeters	Internal + external
γ Rays	Electromagnetic ray	Many meters	Many centimeters	Internal + external
X-rays	Electromagnetic ray	Many meters	Many centimeters	External
Protons	Free proton	Few to many centimeters	Few to many centimeters	External
Neutrons	Free neutrons	Many meters	Many centimeters	External
α Particles	2 Protons + 2 neutrons (helium)	Few centimeters	Cannot penetrate skin	Internal
High charge and energy (HZE) nuclei	Nuclei of atoms with n-neutrons and z-protons	Few to many centimeters	Few to many centimeters	External

[a]The hazard site refers to whether the radiation type exerts its effect only on ingestion or inhalation (internal), or whether it can penetrate the human body (external).

several mean free paths the primary GCR heavy ions are converted largely into protons and neutrons. On entering the Earth's atmosphere, the particles collide with the nuclei of nitrogen, oxygen, and other atmospheric atoms, generating additional (secondary) ionizing radiation particles. At normal commercial aircraft flight altitudes, this GCR consists mainly of neutrons, protons, electrons, positrons, and photons.

Figure 8-1 illustrates the production of secondary particles as a primary particle penetrates the Earth's atmosphere and interacts with an atmospheric nucleus.

Terrestrial Protection from Galactic Cosmic Radiation

Protection from cosmic radiation for the Earth's inhabitants is provided by three variables:

1. The sun's magnetic field and solar wind (solar cycle)
2. The Earth's magnetic field (latitude)
3. The Earth's atmosphere (altitude)

1. The sun has a varying magnetic field with a basic dipole component that reverses direction approximately every 11 years. Recently solar maximum period peaked around 2000 to 2002 and the next one is expected around 2011. Near the reversal, at "solar minimum" (around 2006 in the current cycle), there are few sunspots and the magnetic field extending throughout the solar system is relatively weak and smooth. At solar maximum, there are many sunspots and other manifestations of magnetic turbulence, and the plasma of protons and electrons ejected from the sun (the solar wind) carries a relatively strong and convoluted magnetic field with it outward through the solar system (4).

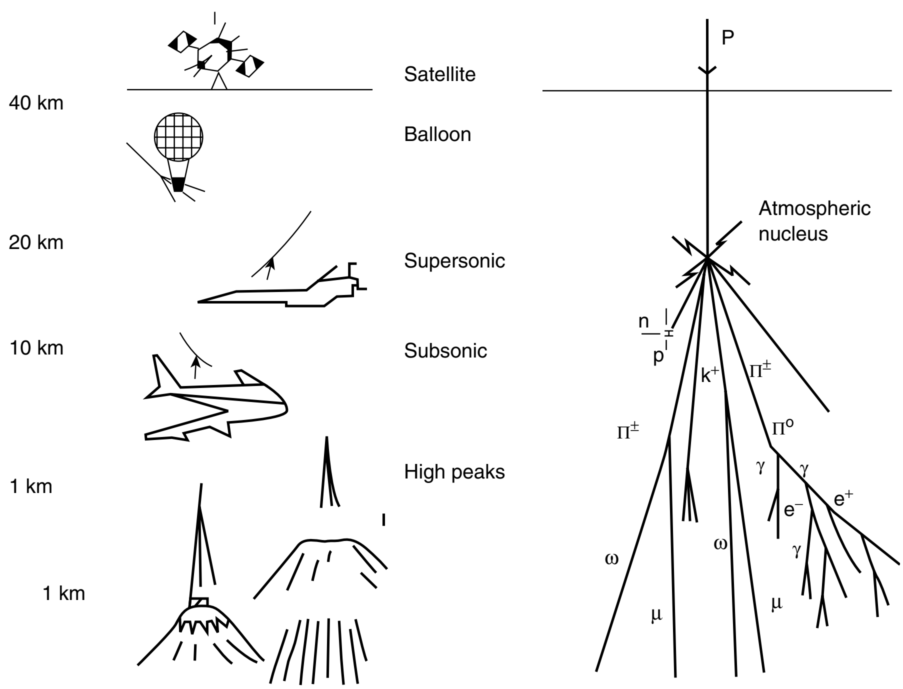


FIGURE 8-1 Production of secondary particles in the atmosphere.

When the solar magnetic field is stronger, the paths of the electrically charged ions are deflected further and less GCR reaches the Earth. Therefore, solar maximum causes a radiation minimum and, conversely, solar minimum is the time of radiation maximum. The effect of this depends on the other two variables, altitude and geomagnetic latitude. At the altitudes flown by commercial jet aircraft and at polar latitudes, the ratio for GCR at solar minimum to that at solar maximum is in the region of 1.2 to 2 and increases with altitude (5,6).

2. The Earth's magnetic field has a larger effect than the sun's magnetic field on cosmic radiation approaching the atmosphere.

Near the equator, the geomagnetic field is almost parallel to the Earth's surface. Near the magnetic poles, the geomagnetic field is nearly vertical and the maximum number of primary cosmic rays can reach the atmosphere. At extremes of latitude, there is no further increase in GCR flux with increasing latitude and this is known as the *polar plateau*.

As a result, cosmic radiation levels are higher in polar regions and decline toward the equator, the size of this effect being dependent upon altitude and the point in the solar cycle. At the altitudes flown by commercial jet aircraft, at solar minimum, GCR is 2.5 to 5 times more intense in polar regions than near the equator, with larger latitude dependence as altitude increases (7).

3. Life on Earth is shielded from cosmic radiation by the atmosphere.

Charged cosmic radiation particles lose energy as they penetrate the atmosphere by ionizing the atoms and molecules of the air (releasing electrons). The particles also collide with the atomic nuclei of nitrogen, oxygen, and other atmospheric constituents.

Ambient radiation increases with altitude by approximately 15% for each increase of approximately 2,000 ft (~600 m) (dependent on latitude), with certain secondary particles reaching a maximum at approximately 65,000 ft (20 km) (the Pfotzer maximum). Primary heavy ions and secondary fragments become important above this point.

In addition to providing shielding from GCR, the atmosphere contributes different components to the radiation flux as a function of atmospheric depth. Accordingly, the potential biological effects of cosmic radiation on aircraft occupants are directly altitude dependent. Dose rate increases with both altitude and latitude. The effect of increasing latitude at a constant altitude is greater than that of increasing altitude at a constant latitude.

Figure 8-2 shows the calculated effective dose rate from each of the secondary components produced by GCR (and the total effective dose) as a function of altitude for a location at the edge of the polar plateau during solar minimum (radiation maximum) (4).

It can be seen that the total effective dose rate at 30,000 ft is approximately 90 times the rate at sea level. It increases by a factor of 2 between 30,000 ft and 40,000 ft, and by another factor of 2 between 40,000 ft and 65,000 ft. It should be noted

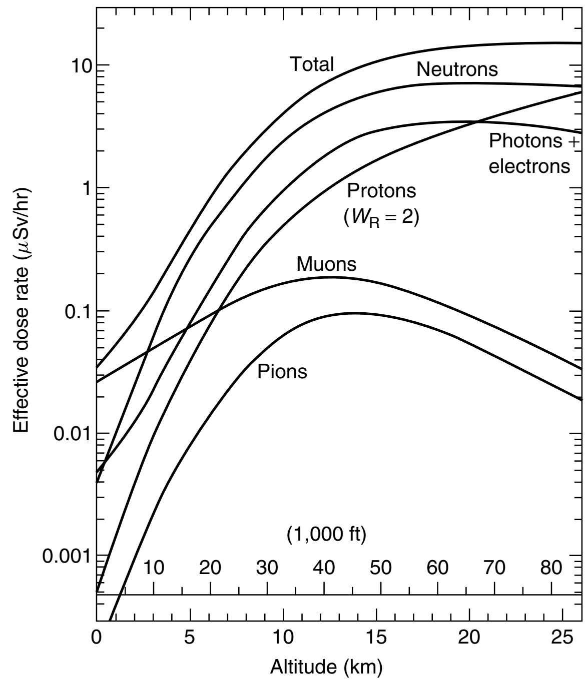


FIGURE 8-2 Calculated effective dose rate as a function of altitude for various component particles of galactic cosmic radiation in the atmosphere near the plar plateau (cutoff = 0.8 GV) at solar minimum (June 1997). Data are courtesy of K. O'Brien, calculated using his LUIN-98F radiation transport code, but with W_R for protons set equal to 2 (NCRP 1993) rather than 5. (Reproduced from Goldhagen P. Overview of aircraft radiation exposure and recent ER-2 measurements. *Health Phys* 2000;79(5):586–591, the journal Health Physics with permission from the Health Physics Society and the National Council on Radiation Protection and Measurements.)

that at all altitudes from 10,000 ft to more than 80,000 ft (3 to 25 km) neutrons are the dominant component. They are less dominant at lower latitudes, but still contribute 40% to 65% of the total dose equivalent rate.

Solar Flares

Occasionally a disturbance in the sun's atmosphere, known as a *solar particle event*, leads to a surge of radiation particles. These are produced by sudden sporadic releases of energy in the solar atmosphere (solar flares) and by coronal mass ejections (CMEs), and are usually of insufficient energy to contribute to the radiation field at aviation altitudes. However, on occasions proton particles are produced with sufficient energy to penetrate the Earth's magnetic field and enter the atmosphere. These particles interact with air atoms in the same way as GCR particles. Such events are comparatively short lived and vary with the 11-year solar cycle, being more frequent at solar maximum.

Long-distance radio communications are sometimes disrupted because of increased ionization of the Earth's upper atmosphere by x-rays, protons or ultraviolet radiation from the sun. This can occur in the absence of excessive ionizing radiation levels at commercial flight altitudes. Similarly the Aurorae Borealis and Australis (northern and southern lights), while resulting from the interaction of charged particles with air in the upper atmosphere, are not an indication of increased ionizing radiation levels at flight altitudes.

When primary solar particle energies are sufficient to produce secondary particles detected at ground level by neutron monitors, this is known as *ground level enhancement* (GLE). GLEs are rare, averaging approximately 1/yr grouped around solar maximum, and the spectrum varies between events (8). Any rise in dose rates associated with an event is rapid, usually taking place in minutes. The duration may be hours to several days.

The strong magnetic disturbance associated with SPEs can lead to significant decreases in GCR dose rate over many hours as a result of the enhanced solar wind (Forbush decrease). The disturbance to the geomagnetic field can allow easier access to cosmic rays and solar particles. This can give significant increases at lower latitudes particularly for SPEs. Therefore, the combined effect of an SPE may be a net decrease or increase in radiation dose, and further work is needed to understand the contribution of SPEs to dose. Prediction of which SPEs will give rise to significant increases in radiation dose rates at commercial aircraft operating altitudes is not currently possible, and work continues with this aspect of space weather.

GLEs have been recorded and analyzed since 1942, and are numbered sequentially (9). Of the 64 GLEs observed up to 2003, with the exception of GLE5 (February 1956), none has presented any risk of attaining an annual dose of 1 mSv (the *International Commission on Radiological Protection* [ICRP] recommended public exposure limit) (10). For GLE60, which occurred in April 2001, the total contribution to radiation dose from the SPE was measured as 20 μSv (11).

GLE42, which occurred in September 1989, was the most intense observed since that of 1956 (GLE5) with a recorded magnitude of 252%. However, this represented approximately 1 month of GCR exposure only, which would not have given an annual dose in excess of 1 mSv (12). Concorde supersonic transport aircraft of British Airways were flying during this solar event and the on-board monitoring equipment did not activate a radiation warning alert, which is triggered at 0.5 mSv/hr. However, it should be cautioned that the latitude effect exceeds the altitude effect for SPEs and Concorde did not reach very high magnetic latitudes.

It has been reported (10) that a number of airlines have changed flight plans to avoid high geomagnetic latitudes during periods of predicted solar flare ground level events, with significant cost and delays to service. Data indicate that these actions were unnecessary in terms of radiation dose protection.

RADIOBIOLOGY

Biological Effects of Ionizing Radiation

Very high levels of ionizing radiation, such as that from a nuclear explosion, will cause severe cell damage or cell death. Adverse health impacts include early death, within days or a few weeks, as a result of acute exposure whereas longer-term consequences include development of cancer, or genetic maldevelopment as a result of damage to the reproductive cells. It is more difficult to predict the effects of low-level doses of ionizing radiation such as cosmic radiation or medical x-rays because of the individual variability in the body's self-repair processes. Indeed, several health effects have been suggested at low doses and dose rates, including that the effect of radiation on human health is not linear, but is either a J-shaped curve with exposure being beneficial at low doses (13,14); or in contrast is increased due to nontargeted effects where cells not directly traversed by radiation tracks are responsible for malignancy (15,16).

Biological effectiveness depends on the spatial distribution of the energy imparted and the density of the ionizations per unit path length of the ionizing particles. The energy loss per unit path length of a charged particle is referred to as the *stopping power*, whereas the energy deposited is referred to as *linear energy transfer* (LET).

The ionization process in living tissues consists of atomic and molecular excitations, and ejecting bound electrons from the cellular molecules, leaving behind chemically active radicals that are the source of adverse changes. Many of the radicals resulting from radiation injury are similar to those produced in normal metabolic processes, for which the cell has developed recovery mechanisms needed for long-term survival (17). The number of ionization events per particle passage is related to the physical processes by which particle kinetic energy is transferred to the cellular bound electrons (2). The rate at which ions produce electrons in isolated cells is important because repair of a single event is relatively efficient unless many events occur within the repair period (14).

The substantive target of radiation injury is considered to be the DNA structure that may be changed or injured directly by a passing ionizing particle (2). DNA damage consists of simple types with a single base damage or break in the DNA sugar-phosphate backbone, termed a *single strand break*, to complex types where two or more damages occur in a single helical turn of DNA. The spectrum of DNA damages shifts from simple to more complex as the LET is increased (18). Double-strand breaks (DSB), defined as one or more breaks on opposing sides of the DNA sugar-phosphate backbone within 20 base pairs of each other, are expected to be the most detrimental form of DNA damage leading to various forms of mutation including gene deletion and chromosomal aberrations. For high-LET radiation, most DSB are highly complex involving base damage and other breaks near a DSB.

The ability of the cell to repair the effects of ionization depends on the class of DNA lesion (simple or complex) and in part on the number of such events occurring within the cell from the passage of a single particle, and the rate at which such passages occur. There are two major pathways of DSB repair in vertebrae (19): (i) nonhomologous end-joining (NHEJ) and (ii) homologous recombination (HR). NHEJ is an error-prone form of repair and is dominant in the prereplication phase of the cell cycle and in resting cells. This process involves removal of damaged regions near the initial break and ligation of the remaining DNA ends. HR is a high-fidelity form of DNA damage repair, acting during DNA replication and mitosis, and requires a sister chromatid to act as a template for the synthesis of DNA during repair.

In recent years, there has been increased focus on non-DNA targets for harmful biological effects of radiation (15, 16). These include oxidative damage in the cytoplasm and mitochondria, and aberrant cell signaling processes that disrupt normal cellular processes such as the control of cellular growth factors, the tissue microenvironment, and DNA replication. These so-called nontargeted effects can be both mutagenic and carcinogenic.

Chromosome Aberrations

Tissue cells may be damaged by physical agents such as heat, cold, vibration, and radiation. Throughout life, there is a continuous ongoing cycle of cell damage and repair utilizing the body's self-repair mechanisms. During the repair process, gene translocation and other chromosome aberrations may occur.

A number of studies have identified an increased rate of unstable chromosome aberrations such as dicentrics and rings in flight crewmembers, and related these to cosmic radiation exposure (20–22). Nicholas et al. noted that unstable aberrations decrease with time and therefore do not serve as good indicators of cumulative exposure to GCR. They postulate that structural chromosome aberrations such as translocations may be a better marker because they are relatively stable over time since exposure (23). Nicholas et al. also showed that the mean number of translocations per cell was significantly higher among the airline pilots who were studied compared to controls. However, within the radiation exposure range encountered in the study, observed values among the pilots did not correspond to the dose–response pattern expected on the basis of available models for chronic low-dose radiation exposure. In addition, this study does not determine the role of radiation in the induction of translocations and so far, no epidemiologic evidence links these aberrations with the development of cancers.

Studies of chromosome aberrations with high-LET radiation, including heavy ions, show that the complexity of chromosome aberrations also increases with LET (24). These studies are made using multicolor fluorescence *in-situ* hybridization (FISH), where chromosome-specific probes are used to label individual chromosomes, and aberrations between two or more chromosomes are observed after irradiation as illustrated in Figure 8-3. The number of chromosomes involved in chromosomal aberrations appears to increase with the LET of the radiation field. George et al. (25) reported the number and types of chromosomal aberrations in astronauts on the International Space Station (ISS).

The biological effect of ionizing radiation depends upon whether it is high or low LET. Early studies of the effect of identical doses of different types of radiation on biological systems showed that different amounts of damage were produced. This led to the concept of "relative biological effectiveness" (RBE), which is defined as the ratio of a dose of a particular type of radiation to the dose of γ rays or x-rays that yield the same biological endpoint.

The dose equivalent to the tissue (DE) is the product of the absorbed dose (D) and the quality factor (Q or QF), Q being dependent upon LET. The numerical value of Q depends not only on appropriate biological data but also on the judgment of the ICRP. It establishes the value of the absorbed dose of any radiation that engenders the same risk as a given absorbed dose of a reference radiation (26). The radiation weighting factor (W_R) takes account of quality factor, and recommendations are published from time to time by the ICRP (26).

Low-LET radiation, all with a weighting factor of 1, includes photons, x- and γ rays, as well as electrons and muons. Electrons are the low-LET radiation of prime concern at aircraft operating altitudes.

Neutrons, α-particles, fission fragments and heavy nuclei are classified as high LET, with neutrons providing approximately half the effective dose at high altitudes.

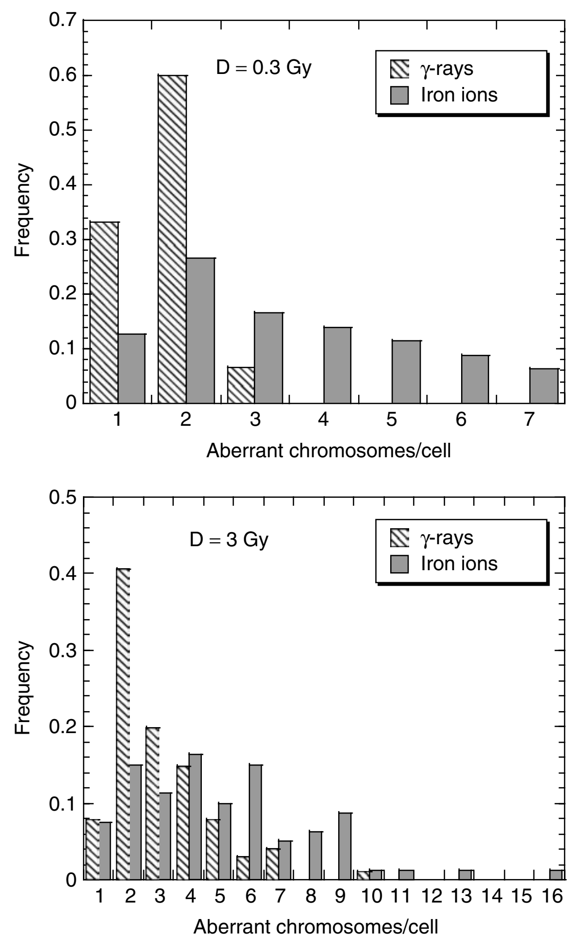


FIGURE 8-3 Observation of chromosomal aberrations in human lymphocyte cells exposed to 300 mGy of γ rays or 1 GeV/u iron ions. (Durante M, George K, Wu H, et al. Karyotypes of human lymphocytes exposed to high-energy iron ions. *Radiat Res* 2002;158:581–590.)

TABLE 8-2

Radiation Weighting Factors

Type and Energy Range of Incident Radiation	*Weighting Factor*
Photons (all energies)	1
Electrons and muons (all energies)	1
Protons (incident)	5[a]
Neutrons <10 keV	5
Neutrons 10–100 keV	10
Neutrons >100 keV–2 MeV	20
Neutrons >2–20 MeV	10
Neutrons >20 MeV	5
α Particles, fission fragments, heavy ions	20

[a]The ICRP has proposed that the weighting factor for protons should be reduced from a value of 5 (as recommended in ICRP Publication 60, 1991) to a value of 2.

(ICRP Publication 92: Relative Biological Effectiveness, Quality Factor, and Radiation Weighting Factor, 92. Elsevier, 2003.)

At all altitudes from 10,000 ft to more than 80,000 ft (3–25 km) neutrons are the dominant component of the cosmic radiation field. They are less dominant at lower latitudes, but still contribute 40% to 65% of the total dose equivalent rate. Because neutron interactions produce low-energy ions, neutron radiation is more effective in inducing biological damage than γ radiation. However, there are no adequate epidemiologic data to evaluate to what extent neutrons are carcinogenic to humans (27).

The current weighting factors are shown in Table 8-2. The weighting factor for neutrons depends on the energy of the incident neutrons. ICRP Publication 92 proposes that the means of computation of the factor should be a continuous function of energy rather than the step function given in Publication 60 (26).

These proposals are based on current knowledge of biophysics and radiobiology, and acknowledge that judgments about these factors may change from time to time.

(ICRP recommends that no attempt be made to retrospectively correct individual historical estimates of effective dose or equivalent dose in a single tissue or organ. Rather the revised weighting factor should be applied from the date of adoption.)

Radiation Units of Measurement

The standard unit of radioactivity is the Becquerel (Bq), which is defined as the decay of one nucleus per second.

When considering cosmic radiation the practical interest is in the biological effect of a radiation dose, the dose equivalent being measured in Sievert (Sv). The ICRP has recommended a number of quantities based on weighting absorbed dose, to take account of the RBE of different types of radiation. Dose equivalent (Sv) is one of these.

Dose equivalent (H) is defined as:

$$H(\text{LET}) = Q(\text{LET}) \times D(\text{LET})$$

where Q is the quality factor and is a function of LET, and D is the absorbed dose.

The effective dose is obtained by the use of absorbed dose, D, along with different weighting factors for organs and tissues.

Doses of cosmic radiation are of such a level that values are usually quoted in microSievert (μSv) per hour or milli-Sievert (mSv) per year (1 mSv = 1,000 μSv).

The Sievert has superseded the rem as the unit of measurement of effective dose (1 Sv = 100 rem, 1 mSv = 100 mrem, 1 μSv = 0.1 mrem).

Other Terrestrial Sources of Ionizing Radiation

There is a constant background flux of ionizing radiation at ground level. Terrestrial background radiation from the Earth's materials contributes 2.6 mSv/yr in the United Kingdom and 3 mSv/yr in the United States (28). This flux is dominated by the low-LET component (93%).

Inhaled radon gas contributes approximately 2 mSv/yr to the total overall background ionizing radiation level (28).

Medical x-rays are delivered in a concentrated localized manner, and usual doses are of the order (28):

Chest x-ray	0.1 mSv (100 μSv)
Body computed tomographic (CT) scan	10 mSv
Chest CT scan	8 mSv
Intravenous pyelogram (IVP)	1.6 mSv
Mammogram	0.7 mSv (700 μSv)

These are effective doses averaged over the entire body, accounting for the relative sensitivities of the different tissues exposed.

Doses received from radiotherapy for cancer treatment range from 20 to 80 Sv (29). These are all average figures with wide individual variations.

Radiological Protection

Workers in the nuclear industry and those who work with medical x-rays may be designated as "classified workers" and have their occupational radiation exposure monitored and recorded. For classified workers, the ICRP recommends maximum mean body effective dose limits of 20 mSv/yr (averaged over 5 years, with a maximum in any 1 year of 50 mSv), with an additional recommendation that the equivalent dose to the fetus should not exceed 1 mSv during the declared term of the pregnancy. This limit for the fetus is in line with the ICRP recommendation that the limit for the general public should be 1 mSv/yr (30).

Workers in the nuclear industry and in medical physics are at potential risk of accidental high exposure, and radiologic protection regulations require that they be educated to take every effort to avoid such accidents. The situation differs in the aerospace environment where exposure to radiation is not the result of an accident and is unavoidable.

In the United Kingdom, the National Radiological Protection Board (NRPB) recommends that a record be

TABLE 8-3

Summary of Maximum Mean Effective Dose Limits

	ICRP	*EU*	*FAA*
General public	1 mSv/yr	1 mSv/yr	1 mSv/yr
Occupationally exposed	20 mSv/yr, 5-yr average, but not more than 50 mSv in 1yr	20 mSv/yr, 5-yr average, but not more than 50 mSv in 1yr	20 mSv/yr, 5-yr average, but not more than 50 mSv in 1yr
Fetus equivalent dose	1 mSv/yr	1 mSv for declared term of pregnancy and ALARA	1 mSV maximum, but 0.5 mSv in any month
Control level	N/A	6 mSv	N/A

ICRP, International Commission for Radiological Protection; EU, European Union; FAA, Federal Aviation Administration; ALARA, as low as reasonably achievable.

kept of exposure rates and there should be a systematic assessment of the individual dose of any worker considered likely to receive an effective dose of more than 6 mSv/yr, this being referred to as the *control level*. This value is a cautious arbitrary figure, representing three tenths of the annual maximum for classified workers and has no radiobiological significance (31).

In 1991, the ICRP recommended that exposure of flight crewmembers to cosmic radiation in jet aircraft should be considered part of occupational exposure to ionizing radiation (30).

In 1994, the United States Federal Aviation Administration (FAA) formally recognized that air carrier aircrews are occupationally exposed to ionizing radiation, and recommended that they be informed about their radiation exposure, associated health risks, and that they be assisted in making informed decisions with regard to their work environment (32). The FAA subsequently issued a technical report in October 2003 advising aircrew about their occupational exposure to ionizing radiation (33). The FAA recommends the limit for an aircrew member of a 5-year average effective dose of 20 mSv/yr, with no more than 50 mSv in a single year (34). For a pregnant aircrew member starting when she reports her pregnancy to management, the recommended limit for the conceptus is an equivalent dose of 1 mSv, with no more than 0.5 mSv in any month (34).

Following the ICRP recommendation, the Council of the European Union (EU) adopted a directive laying down safety standards for the protection of the health of workers and the general public against the effects of ionizing radiation (35). Article 42, which deals with protection of aircrew, states that for aircrew who are liable to be subject to exposure of more than 1 mSv/yr appropriate measures must be taken. In particular, the employer must perform the following functions:

- Assess the exposure of the crew concerned.
- Take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed aircrew.
- Inform the workers concerned of the health risks their work involves.
- Apply special protection for female aircrew during declared pregnancy

The European Directive applies the ICRP limits for occupational exposure (20 mSv/yr) and the 1-mSv exposure limit to the fetus for the duration of declared pregnancy. In addition, the European Directive indicates that radiation exposure to a pregnant crewmember should be "as low as reasonably achievable" (ALARA) (35). This was transformed into national law of the EU member states in May 2000.

Both the European Directive and the FAA Technical Report follow the ICRP recommended limits for occupational exposure, but there are differences for pregnancy. The European Directive uses the "ALARA" principle in recommending that radiation exposure to the pregnant worker should be ALARA, with an absolute maximum of 1 mSv. However, the FAA recommends a maximum dose to the fetus of 1 mSV but allows 0.5 mSv in any month, making no reference to ALARA. Maximum mean effective dose limits are summarized in Table 8-3.

Health Risks of Cosmic Radiation

1. ***Development of cancer.*** A cell may become cancerous as a result of being irradiated, the likelihood being dependent upon the energy and the dose received. For an accumulated cosmic radiation dose of 5 mSv/yr over a career span of 20 years (a typical prediction for a long-haul crewmember), the likelihood of developing cancer will be 0.4% (33,36). The overall risk of cancer death in the western population is 23%, so the cosmic radiation exposure increases the risk of cancer death from 23% to 23.4% (33,36). For a career span of 30 years, the cancer risk increases from 23% to 23.6%.
2. ***Genetic risk.*** A child conceived after exposure of a parent to ionizing radiation is at risk of inheriting radiation-induced genetic defects. These may take the form of anatomic or functional abnormalities apparent at birth or later in life. The risk following an accumulated dose of 5 mSv/yr over a career span of 20 years will be 1 in 2,510 (33). For a 30-year career, the risk increases to 1 in 1,700. Again, this needs to be considered against a background incidence in the general western population

of approximately 1 in 51 for genetic abnormalities, with 2% to 3% of liveborn children having one or more severe abnormalities at birth (33).

3. ***Risk to the health of the fetus.*** The risks to the fetus from ionizing radiation are cancer and mental retardation. There is a background rate of approximately 1 in 39,000 for neonatal lymphoblastic leukemia and 1 in 170 for childhood mental retardation within the general population. It is estimated that exposure of the fetus to cosmic radiation for 80 block hours/mo will increase the risk by between 1 in 6,000 and 1 in 30,000 depending on the routes flown. The increased lifetime risk of fatal cancer from 1 mSv received during prenatal development is 1 in 10,000 (0.01%) (33).
4. ***Noncancer effects (degenerative tissue risks).*** The most important of the noncancer risks due to radiation exposure are degenerative diseases including heart and digestive diseases, early and late effects in the central nervous system, and cataracts. Noncancer effects are thought to be deterministic in nature, occurring only above a dose threshold well above aviation doses and most space missions, except for a Mars mission or extraterrestrial exposure to a large SPE. However, recent epidemiologic studies (37,38) indicate threshold concepts do not seem to hold, indicating these risks are a concern for spaceflight.

COSMIC RADIATION IN COMMERCIAL AVIATION

Measurement of Cosmic Radiation Doses in Aviation

The ICRP 1991 recommendations require that cosmic radiation exposure for flight crewmembers should be assessed and recorded (30). It has been seen that the GCR field at aircraft operating altitudes is complex, with a large energy range and the presence of all particle types. The Concorde supersonic transport aircraft first flew in 1969 and entered service with Air France and British Airways in 1976, retiring in 2003. From the outset, it was appreciated that cosmic radiation (both galactic and solar) could present a hazard at the operating altitude of approximately 60,000 ft (18 km). Accordingly, ionizing radiation monitoring equipment was permanently installed in all Concordes and much data were derived (39–43).

The introduction of aircraft such as the Boeing 747-400 and the Airbus A330 and A340 has led to the development of ultralong haul flights of up to 18 hours duration with the potential for even longer flight times. Many of the routes flown are trans-Polar or trans-Siberian, where geomagnetic and, to a lesser extent, atmospheric shielding from GCR are less than for routes at lower latitudes.

GCR can be measured actively or passively. Many detectors measure only one type of radiation accurately and usually for only a limited energy range, but they may show some sensitivity to other types of radiation. An active direct reading instrument displays the appropriate values immediately or after a short delay, whereas passive integrating instruments need to be evaluated in a laboratory after the flight.

A number of studies have been published giving effective dose rates for subsonic flights, measured both actively and passively (5,11,36,39,40,44–51). These values are discussed in the next section.

Effective dose cannot be measured directly, but ambient dose equivalent, which is a measured operational quantity, can be a good estimator of the effective dose received from cosmic radiation. (See section **Radiation Units of Measurement**) Calculations of ambient dose equivalent rate or route doses can be validated by direct measurement.

Concorde was the only commercial aircraft to be equipped with radiation dosimeters measuring data for the duration of every flight. On the basis of data derived from these measurements, cost–benefit analysis makes it difficult to justify the cost of installation, calibration, and maintenance for such equipment in the worldwide fleet of subsonic aircraft.

It is frequently suggested that individual dosimeters in the form of film badges should be worn by crewmembers. However, the sensitivity of such passive dosimeters is very low and the badges would have to be worn for several sectors for meaningful data to become available. Lantos et al. reported that during an experiment involving crew members voluntarily wearing personal dosimeters, 8% of the badges were lost or not used and 2% had received additional x-rays during baggage security screening (12). The logistics and costs of issuing, tracking, and processing many thousands of film badges within a commercial airline operation are prohibitive.

Computer programs have been developed for the calculation of effective dose from GCR, taking account of the following factors:

- Geographic coordinates of origin and destination airports
- Longitude and latitude of all points of the aircraft's track
- Altitude at all times of the flight
- Helicocentric potential, to account for solar activity
- Date and time of flight
- Quality of the radiation field through which the aircraft flies

The most widely used program is CARI-6, developed by the U.S. FAA based on the LUIN transport code (52). It is limited to the galactic cosmic ray component, which is isotropic and of constant spectrum outside of the heliosphere. The CARI program has been validated by in-flight measurement and found to be accurate to within ±7% (12). However, other workers question this accuracy because of the uncertainty associated with the contribution of solar particles. There is a freely available interactive version of CARI-6, which runs on the Internet and is publicly accessible (http://www.cami.jccbi.gov/radiation.html). There is also a more sophisticated downloadable version, which allows the user to store and process multiple flight profiles and to calculate dose rates at user-specified locations in the atmosphere.

Another package, European Programme Package for the Calculation of Aviation Route Doses (EPCARD), has been developed on behalf of the European Commission (53). This is based on the FLUKA transport code (54) and is again limited to the galactic cosmic ray component, which is isotropic and of constant spectrum outside of the heliosphere. The Systeme d'Information et d'Evaluation par Vol de l'Exposition au Rayonnement cosmique dans les Transport aeriens (SIEVERT) system which has been developed on behalf of the French Aviation Administration (DGAC) (12) is freely available (http://www.sievert-system.org). A similar validated Canadian program is known as *PCAIRE* and is also freely available (www.pcaire.com) (46).

These computer programs allow airline companies and their employees to comply with the ICRP recommendations to monitor radiation exposure. European airlines have a statutory duty to comply with the ICRP recommendations as a result of the EU Directive (see the preceding text). However, elsewhere in the world there is no legal requirement for airlines to follow the ICRP recommendation.

Cosmic Radiation Doses Received by Aircraft Occupants

There have been many studies of cosmic radiation dose rates in both Concorde and subsonic aircraft (5,11,36,39,40,44–51,53,55), all giving similar results. European airlines have been required to monitor and record occupational exposure since May 2000 to comply with the European Directive. This is achieved using computer programs discussed in the preceding text such as CARI, EPCARD, SIEVERT, or PCAIRE, periodically validated by on-board measurement of the radiation field.

Exposure depends on the route, altitude, and aircraft type (which influences rate of climb and descent) and is usually quoted as microSievert (μSv) per block hour (block hours are based on the time from when the aircraft first moves under its own power to the time of engine shut-down at the end of the flight). Short-haul operations tend to fly at lower altitudes than long haul, gaining the benefit of atmospheric shielding as well as a shorter duration of exposure. Conversely, many long-haul routes are flown at higher latitudes as well as at higher altitudes.

For operations in the northern hemisphere, mean ambient equivalent dose rates have been measured in the region of:

- Concorde: 12–15 μSv/hr
- Long haul: 4–5 μSv/hr
- Short haul: 1–3 μSv/hr

In general, for UK-based crewmembers operating to the maximum flight time limitations of 900 hr/yr, it is calculated that:

- Long-haul crew have an annual mean effective exposure of 2 to 4 mSv/yr, less than one fifth of the ICRP recommended dose limit
- Short-haul crew have an annual mean effective exposure of 1 to 2 mSv/yr, less than one tenth of the recommended dose limit

On the worst-case U.K. high-latitude polar routes, such as London Heathrow to Tokyo Narita, the mean ambient equivalent dose rate has been measured at 6 μSv/hr (5). For a crewmember flying 900 hr/yr only on this route, the annual exposure would be in the region of 5.4 mSv, less than three tenths of the ICRP recommended dose limit of 20 mSv. For ultra–long range airline operations (arbitrarily defined as sector lengths in excess of 18 hours), recent studies (55) have shown a mean effective sector exposure of 80 μSv on the Dubai to Los Angeles route. A crew member flying three return trips per month would accrue an annual exposure of 5.76 mSv. The FAA has calculated the worst-case U.S. high altitude, high-latitude long-haul flight to be New York to Athens, with an equivalent dose of 6.3 μSv/hr (33)

For a pregnant crewmember working on this worst-case route, she could work 79 block hours each month without the dose to the conceptus exceeding the FAA monthly recommended limit of 0.5 mSv ($0.5/0.0063 = 79$). She could work 2 months without the dose to the conceptus exceeding the recommended pregnancy limit of 1 mSv ($1/0.5 = 2$).

A number of airlines require crewmembers to cease flying on declaration of pregnancy, in conformity with the European Directive requirement for the radiation exposure to the fetus to be as low as reasonably achievable (56). The policy of the FAA is that crewmembers must be provided with information about cosmic radiation, but there is no statutory requirement for them to stop flying.

For passengers, the ICRP limit for the general public of 1 mSv/yr would have equated to approximately 100 hours of flying per year on Concorde, and equates to approximately 200 hr/yr on trans-Equatorial subsonic routes (42).

There are essentially two types of airline passenger—the occasional social traveler and the frequent business traveler. The public limit of 1 mSv/yr will be of no consequence to the former, but could be of significance to the frequent business traveler who would exceed the 1 mSv limit if flying more than eight transatlantic or five UK-Antipodean return subsonic journeys per year (42). However, business travelers are exposed to radiation as an essential part of their occupation and it is logical to apply the occupational limit of 20 mSv to this group. This view has the support of the ICRP (57). Although business travellers may exceed the doses for aircrew, there is no mechanism in place to monitor or control their exposure.

Epidemiology of Commercial Aircraft Crew Members

The annual aircrew dose of cosmic radiation is a relatively low level of overall exposure, with the maximum being no more than two or three times the annual level of exposure to background radiation at ground level. There have been a number of epidemiologic surveys of cancer mortality and incidence in commercial flight crewmembers over the years, which have reported small excesses of a variety of cancers (58,59). However, the results have lacked consistency. This lack of consistency mainly derives from the small size of cohorts examined and the lack of data on exposure and confounding factors that might explain the findings.

In Europe two large mortality cohort studies, one amongst flight deck crew (60) and one amongst cabin crew (61), together with a large cancer-incidence study amongst Nordic pilots (62) have been published. They are based on data from many of the individual studies in the literature but contain additional data, providing increased statistical power in looking at small excesses, allow measures of consistency between studies to be determined, and provide the basis for dose–response assessments.

Both the Blettner et al. paper (60), which looked at 28,000 flight deck crew with 591,584 person-years at risk, and the Pukkala et al. paper (62), comprising 177,000 person-years at risk from 10,211 pilots, concluded that occupational risk factors were of limited influence on the findings. There was consistency though in the mortality study showing an excess of malignant melanoma. In the incidence study, this excess referred to both malignant melanoma and other forms of skin cancer as well. Blettner concluded that the excess melanoma incidence may be attributable to ultraviolet radiation, perhaps due to leisure-time sun exposure, but more work is required. Pukkala et al. (62) concluded that although the risk of melanoma increased with estimated dose of ionizing radiation, the excess might well be attributable to solar ultraviolet radiation.

In the study by Zeeb et al. (61), the excess mortality from malignant melanoma was restricted to male cabin crewmembers.

Several studies in the last decade have suggested a small excess of breast cancer amongst female flight attendants (cabin crew). However, the interpretation has been hampered by sample size and lack of detailed information on confounding factors.

In an attempt to unify the findings, the study by Zeeb et al. (61) examined data from eight European countries. Mortality patterns among more than 51,000 airline cabin crewmembers were investigated, yielding approximately 659,000 person-years of follow-up. Among female cabin crew, overall mortality and all-cancer mortality were slightly reduced, whereas breast cancer mortality was slightly but nonsignificantly increased. The authors concluded that ionizing radiation may contribute in a small way to an excess risk of breast cancer among cabin crew, but the association may be confounded by differences in reproductive factors or other lifestyle factors, such as circadian rhythm disruption.

A study by Raffnson et al. in 2003 based on 35 cases of breast cancer (63), for which more detailed information on reproductive history is available, attempted to further identify the relative contribution of occupation to the excess seen in their earlier cohort study (64). When the results are examined, the risk is seen to be significantly increased only during the period before 1971, when cosmic radiation doses would have been lower due to altitude considerations. No excess is seen in the period after 1971 showing the difficulty of disentangling the contribution of cosmic radiation to the etiology of breast cancer. Overall, the conclusion from Zeeb et al. (61) was that among airline cabin crew in Europe, there was no increase in mortality that could be attributed to cosmic radiation or other occupational exposures to any substantial extent.

A population-based case-controlled study from Iceland by Raffnson et al. in 2005 (65) concluded that the association between the cosmic radiation exposure of pilots and the risk of developing eye nuclear cataracts, adjusted for age, smoking status, and sunbathing habits, indicates that cosmic radiation may be a causative factor in nuclear cataracts among commercial airline pilots. However, the study fails to address the variability in objective assessment of cataracts and the possibility of observer bias. Additionally, a report by Stern from the German Center of Aerospace in 2006 (66) concluded that the occurrence of cataract surgery amongst the German pilot population is smaller than in the normal population, with no cases of pilots having to undergo cataract surgery during their career (other than one case of traumatic cataract). Similar findings are reported by the U.K. Civil Aviation Authority (CAA) (Johnston, RV *personal communication*, 2007). Therefore, any association between exposure of airline pilots to cosmic radiation and the development of cataracts would appear to be weak.

Conclusion for Commercial Aircraft Travellers

While it is known that there is no level of ionizing radiation exposure below which effects do not occur, the evidence so far indicates that the probability of airline crewmembers or passengers suffering any abnormality or disease as a result of exposure to cosmic radiation is very low. Epidemiologic studies of flight deck crew and cabin crew have so far not shown any increase in cancer mortality or cancer incidence that could be directly attributable to ionizing radiation exposure. However, individual mortality studies and combined analyses have shown an excess of malignant melanoma. Separate and combined analyses of cancer incidence have shown an excess for malignant melanoma and for other skin cancers. Many authors believe that the findings can be explained by exposure to ultraviolet light. Others believe that the influence of cosmic radiation cannot be entirely excluded, although no plausible pathological mechanism has been identified.

With respect to the suggestion that cabin crew may be at a higher risk of contracting breast cancer than those females in a nonflying occupation, it is very difficult to effectively disentangle the relative contributions of occupational, reproductive, and other factors associated with breast cancer using the data currently available. Similarly when considering the reported association between cosmic radiation and eye cataracts, it is difficult to exclude observer bias and the influence of sunlight, smoking, dehydration, and diet associated with the protein structure changes in the lens associated with age.

The EU has in place a legislative framework for assessing the cosmic radiation exposure for airline crewmembers, which appears to be effective. Other jurisdictions, such as the United States, rely on advisory material and educational programs. There is a need to improve worldwide consistency, accuracy of calculations, measurements and allowance for, and avoidance of, SPEs.

COSMIC RADIATION IN SPACE FLIGHT

In considering dose limits for astronauts, it is useful to consider historical recommendations that National Aeronautics and Space Administration (NASA) has received from external advisory committees that have formed the basis for dose limits. Recommendations by the National Academy of Sciences (NAS) in 1967 (67) noted that radiation protection in manned space flight is philosophically distinct from protection practices of terrestrial workers because of the high-risk nature of space missions. The report of the NAS from 1967 did not recommend "permissible doses" for space operations, noting the possibility that such limits may place the mission in jeopardy and instead made estimates of what the likely effects would be for a given dose of radiation. In 1970, the NAS Space Science Board (68) made recommendations of guidelines for career doses to be used by NASA for long-term mission design and manned operations. At that time, NASA employed only male astronauts and the typical age of astronauts was 30 to 40 years. A "primary reference risk" was proposed to be equal to the natural probability of cancer over a period of 20 years following the radiation exposure (using the period from 35–55 years of age) and was essentially a doubling dose. The estimated doubling dose of 382 rem (3.82 Sv), which ignored a dose–rate reduction factor, was rounded to 400 rem (4 Sv). The NAS panel noted that the recommendation was not a risk limit, but rather a reference risk and that higher risk could be considered for planetary missions or a lower level of risk for a possible space station (68). Ancillary reference risks were described to consider monthly, annual, and career exposure patterns. However, the NAS recommendations were implemented by NASA as dose limits used operationally for all missions until 1989.

At the time of the 1970 NAS report the major risk from radiation was believed to be leukemia. Since then, the data from the Japanese atomic bomb (AB) survivors has led to estimates of higher levels of cancer risk for a given dose of radiation including the observation that the risk of solid tumors following radiation exposure occurs with a higher probability than leukemias, although with a longer latency period before expression. Along with the maturation of the AB data and reevaluation of the dosimetry of the AB survivors, scientific assessments of the dose–response models, and dose-rate dependencies have contributed to the large increase in the risk estimate over this time period (1970–1997). The possibility of future changes in risk estimates cannot of course be safely predicted now. Therefore, protection against uncertainties is an ancillary condition to the ALARA principle, suggesting conservatism as workers approach dose limits.

By the early 1980s several major changes had occurred leading to the need for a new approach to define dose limits for astronauts. At that time, NASA requested the National Council on Radiation Protection and Measurements (NCRP) to reevaluate dose limits to be used for low Earth orbit (LEO) operations. Considerations included increases in estimates of radiation-induced cancer risks, the criteria for risk limits, and the role of the evolving makeup of the astronaut population from male test pilots to a larger diverse population composed of approximately 100 astronauts including mission specialists, female astronauts, and higher aged career astronauts who often participate in several missions. In 1989, the NCRP Report No. 98 (69) recommended age- and gender-dependent career dose limits using a 3% increase in cancer mortality as a common risk limit. The 3% excess cancer fatality risk was based on several criteria including comparison to dose limits for ground radiation workers and to rates of occupational death in less-safe industries. It was noted that astronauts face many other risks, and adding an overly large radiation risk was not justified. It was also noted that the average years of life loss from radiation-induced cancer death, approximately 15 years for workers older than 40 years and 20 years for workers aged between 20 and 40, is less than that of other occupational injuries. A comparison of radiation-induced cancer deaths to cancer fatalities in the U.S. population is complex because of the smaller years of life loss in the general population due to most cancer deaths occurring above age 70.

In the 1990s, the additional follow-up and evaluation of the AB survivor data has led to further reductions in the estimated cancer risk for a given dose of radiation. The 2000 recommendations from NCRP (70), while keeping the basic philosophy of risk limitation in the earlier report, advocate significantly lower limits than those recommended in 1989 (69). Table 8-4 lists examples of radiation limits for

TABLE 8-4

Career Dose Limits (in Sv) Corresponding to 3% Excess Cancer Mortality for 10-Year Careers As a Function of Age and Sex as Recommended by the National Council on Radiation Protection and Measurements (NCRP, 1989 and NCRP, 2000)

	NCRP Report No. 98		*NCRP Report No.132*	
Age, yr	*Male*	*Female*	*Male*	*Female*
25	1.5 Sv	1.0 Sv	0.7 Sv	0.4 Sv
35	2.5	1.75	1.0	0.6
45	3.2	2.5	1.5	0.9
55	4.0	3.0	3.0	1.7

a career duration of 10 years with the doses assumed to be spread evenly over a career. The values from the previous report are also listed for comparison. Both of these reports specify that these limits do not apply to exploration missions because of the large uncertainties in predicting the risks of late effects from heavy ions.

The NCRP Report No. 132 (70) notes that the use of comparisons to fatalities in the less-safe industries advocated by the NCRP in 1989 is no longer viable because of the large improvements made in ground-based occupational safety. The decreased rate of fatalities in the so-called less-safe industries, such as mining and agriculture, would suggest a limit below the 3% fatality level currently compared to that in 1989. The most recent reviews of the acceptable levels of radiation risk for LEO (70) instead advocate that comparisons to career dose limits for ground-based workers be used. It is also widely held that the social and scientific benefits of space flight continue to provide justification for the 3% risk level for astronauts participating in LEO missions.

Risk projection models serve several roles (71,72); these roles include setting dose-to-risk conversion factors needed to define dose limits, projecting mission risks, and evaluating the effectiveness of shielding or other countermeasures. For mission planning and operations, NASA uses the model recommended in the NCRP Report No. 132 for estimating cancer risks from space (70). This model, which is similar to approaches described by other radiation risk assessment committees and in the scientific literature, employs a life-table formalism. This method consists of epidemiologic assessments of excess risk in exposed cohorts such as the AB survivors, and estimates of dose and dose-rate reduction factors (DDREFs) and LET-dependent radiation quality factors.

Recently, NASA recognized that projecting uncertainties in cancer risk estimates along with point estimates should be a requirement for ensuring mission safety. This is because point estimates alone have limited value when the uncertainties in the factors that enter into risk calculations are large. Estimates of 95% confidence intervals (CI) for various radiation protection scenarios are meaningful additions to the traditional point estimates, and can be used to explore the value of mitigation approaches and of research that could narrow the various factors that enter into risk calculations.

Uncertainties for low-LET radiation, such as γ rays, have been reviewed several times in recent years, and indicate that the major uncertainty is the extrapolation of data on cancer effects from high to low doses and dose rates (73,74). Other uncertainties include the transfer of risk across populations and sources of error in epidemiology data including dosimetry, bias, and statistical limitations. For low-LET radiation, probability distribution functions (PDFs) were described previously (72) and indicate upper 95% CI approximately two times higher than the median risk estimate used in ground-based radiation protection.

In estimating cancer risks for space radiation, additional uncertainties occur related to estimating the biological effectiveness of protons and heavy ions, and to predicting LET spectra at tissue sites (70,71). The limited understanding of heavy ion radiobiology has been estimated to be the largest contributor to the uncertainty for space radiation effects (72), and radiation quality factors are found to contribute the major portion of the uncertainties. For space radiation, upper 95% confidence levels are estimated to be approximately four times higher than the median estimate for GCR, and three times higher for proton exposures from an SPE.

Space Dosimetry

The use of W_R is not used directly at NASA, and instead individual organ dose and dose equivalents are estimated for each astronaut using an approach that relies on available flight dosimetry and transport models of space vehicles and the human body. In this approach W_R are replaced by LET-dependent radiation quality factors and the attenuation of space radiation by the tissue is described (70). The main source of passive dosimetry data are thermoluminescence dosimeters (TLDs) that are worn by each astronaut during his or her mission. In some cases, CR-39 plastic track detectors have been included in the passive dosimetry packages (75). Additional information is obtained by TLDs that are mounted throughout space vehicles such as the space shuttle, space station Mir, and the ISS to survey the variation of point dose dependencies from shielding variations (75).

Tissue equivalent proportional counters (TEPCs) have been flown on some space shuttle missions (76), on the Mir and the ISS. TEPCs (shown in Figure 8-4) are relatively small devices weighing less than 1 kg, providing time-dependent data and a method to estimate the individual contributions from the GCR and trapped proton doses because of the strong geographic dependence of the trapped protons (76,77) in LEO. TEPC data can be used to validate models predicting organ dose equivalents when the models of TEPC response

FIGURE 8-4 The Tissue Equivalent Proportional Counter (TEPC) is an automatic microdosimetry system, which consists of a spectrometer unit and a detector unit. The spectrometer unit contains a computer that allows real-time analysis of the data and provides data on the dose equivalent rate as a function of lineal energy (y) and time for space radiation. The TEPC is filled with a low-pressure gas. TEPCs are also used in aviation.

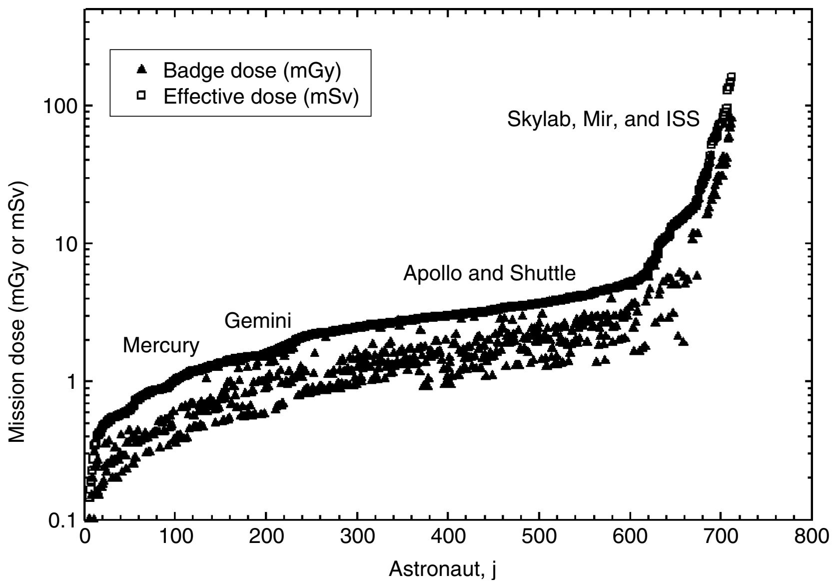


FIGURE 8-5 The badge doses and effective doses versus calendar year from all astronauts on all National Aeronautics and Space Administration (NASA) space missions [Mercury, Gemini, Apollo, Skylab, Apollo-Soyuz, Shuttle, Mir, and ISS (Expedition 1–10)]. (Updated from Cucinotta FA, Wu H, Shavers MR, et al. Radiation dosimetry and biophysical models of space radiation effects. *Gravit Space Biol Bul* 2003;16(2):11–18.)

functions are coupled to space transport models, although not for a direct measurement of mission quality factors. It is estimated that a combined approach using crew dosimetry, worn on the surface of the body, and radiation transport codes to estimate individual organ doses are capable of describing organ dose equivalents with standard errors of less than 10%. Results of this approach for past space missions are shown in Figure 8-5 (78).

Long-term missions on the ISS or the Russian Mir space station have led to crew exposures that exceed 100 mSv. For future missions to Mars, exposures approaching 1,000 mSv or more can be expected. Table 8-5 shows projections for effective doses, risk of exposure-induced death (REID) due to fatal cancer, and 95% confidence levels for 40-year-old men and women for several deep space mission scenarios. Because these risks will be much higher levels than past space missions or ground-based exposures, studies to improve the understanding of the biological effects of space radiation and to develop successful mitigation measures are a primary focus of NASA and other space agencies.

Radiation shielding can be shown to be cost effective for protection against SPEs. In deep space or on the surface of the moon approximately 20 g/cm^2 of aluminium-equivalent material will reduce effective doses from most of the SPE to well below radiation limits. Materials with high hydrogen content such as polyethylene are the most effective in reducing effective doses leading to a significantly reduced mass allotment for radiation shielding compared to traditional spacecraft materials such as aluminum (2,79). The higher energies of GCR compared to solar protons makes shielding an inadequate mitigation approach. Effective doses attenuate quite slowly and the amount of shielding needed

TABLE 8-5

Calculations of Effective Doses, Percentage of Risk of Exposure-Induced Death (REID) from Fatal Cancer, and 95% Confidence Intervals (CI) for Lunar or Mars Missions

Exploration Mission (Length of Mission)	*D (Gy)*	*E (Sv)*	*REID (%)*	*95% CI*
		Males (40 yr)		
Lunar (180 d)	0.06	0.17	0.68	[0.20, 2.4]
Mars swingby (600 d)	0.37	1.03	4.0	[1.0, 13.5]
Mars exploration (1,000 d)	0.42	1.07	4.2	[1.3, 13.6]
		Females (40 yr)		
Lunar (180 d)	0.06	0.17	0.82	[0.24, 3.0]
Mars swingby (600 d)	0.37	1.03	4.9	[1.4, 16.2]
Mars exploration (1,000 d)	0.42	1.07	5.1	[1.6, 16.4]

Calculations are at solar minimum where GCR dose is the highest behind a 5-g/cm aluminum shield. The absorbed dose (*D*) and effective dose (*E*) are averaged over tissues prominent for cancer risks. Competing causes of death are considered in the calculation because for high values of risk they compress the risk probabilities (>5%). (Cucinotta FA, Durante M. Cancer Risk from exposure to galactic cosmic rays: implications for space exploration by human beings. *Lancet Oncol* 2006;7:431–435.)

can be prohibitive. At present, reducing the uncertainties in models of radiation health risk such as carcinogenesis is a focus and is expected to lead to viable biological countermeasure approaches. By elucidating the biological mechanisms underlying radiation-induced cancer, including different mechanisms of action between terrestrial and space radiation types, approaches to intervene and reduce risk are expected to emerge. These studies should be of value for aviation radiation protection as well.

ACKNOWLEDGMENTS

The assistance in epidemiologic interpretation given by Mr. David Irvine, formerly of British Airways, is gratefully acknowledged. Figure 8-2 is reproduced from the journal Health Physics with permission from the Health Physics Society and the National Council on Radiological Protection and Measurements.

REFERENCES

1. Reitz G. Radiation environment in the stratosphere. *Radiat Prot Dosim* 1993;51:3.
2. Wilson JW. Radiation environments and human exposures. *Health Phys* 2000;79(5):510–514.
3. Wilson JW, Townsend LW, Schimmerling W, et al. *Transport methods and interactions for space radiations*. NASA TP-1991-1257.
4. Goldhagen P. Overview of aircraft radiation exposure and recent ER-2 measurements. *Health Phys* 2000;79(5):586–591.
5. Bagshaw M, Irvine D, Davies DM. Exposure to cosmic radiation of British Airways flying crew on ultralonghaul routes. *Occup Environ Med* 1996;53:515–518.
6. Bartlett DT. Cosmic radiation fields at aircraft altitudes and their measurement. *Proceedings of the Royal Aeronautical Society Symposium on In-Flight Cosmic Radiation*. London, 6 February, 1997.
7. Wilson JW, Nealy JE, Cucinotta FA, et al. *Radiation safety aspects of commercial high-speed flight transportation*. Springfield: National Technical Information Service, 1995. NASA Technical Paper 3584.
8. Lovell JL, Duldig ML, Humble J. An extended analysis of the September 1989 cosmic ray ground level enhancement. *J Geophys Res* 1998;103:23733–23742.
9. Duggal SP. Relativistic solar cosmic rays. *Rev Geophys Space Sci* 1979;17(5):1021–1058.
10. Lantos P, Fuller N. Solar radiation doses on board aeroplanes. *Radiat Prot Dosim* 2003;104(3):199–210.
11. Spurny F, Obraz O, Pernicka F, et al. Dosimetry on board subsonic aircraft, CSA flight routes, data and their new interpretation. In: *Proceedings of the 24th Symposium on Radiation Protection Physics*. Gaussig, Germany, 1992.
12. Lantos P, Fuller N, Bottollier-Depois JF. Methods for estimating radiation doses received by commercial aircrew. *Aviat Space Environ Med* 2003;74(7):751–758.
13. Jaworoski Z. *Low level radiation no danger*. http://news.bbc.co.uk/1/hi/health/3595122.stm, accessed 12 August 2004.
14. Taverne D. Nuclear Power is fine–radiation is good for you. *Sunday Telegraph* 2004;20.
15. Park CC, Henshall-Powell RL, Erickson AC, et al. Ionizing radiation induces heritable disruption of epithelial cell interactions. *Proc Natl Acad Sci USA* 2003;100:10728–10733.
16. Mothersill C, Seymour CB. Radiation-induced bystander effects–implications for cancer. *Nat Rev Cancer* 2004;4:158–164.
17. Billen D. Spontaneous DNA damage and its significance for the 'negligible dose' controversy in radiation protection. *Radiat Res* 1990;124:242–251.
18. Goodhead DT. Initial events in the cellular effects of ionising radiation: clustered damage in DNA. *Int J Radiat Biol* 1994;65:7–17.
19. Falck J, Coates J, Jackson SP. Conserved modes of recruitment of ATM, ATR, and DNA-PK_{cs} to sites of DNA damage. *Nature* 2005;434:605–611.
20. Heimers A, Schroder H, Lengfelder E, et al. Chromosome aberration analysis in aircrew members. *Radiat Prot Dosimetry* 1995;60:171–175.
21. Roman E, Ferrucci L, Nicolai F, et al. Increase of chromosomal aberrations induced by ionizing radiations in peripheral blood lymphocytes of civil aviation pilots and crew members. *Mutat Res* 1997;377:89–93.
22. Scheid W, Weber J, Traut H. Chromosome aberrations induced in the lymphocytes of pilots and stewardesses. *Naturwissenschaften* 1993;80:588–530.
23. Nicholas JS, Butler GC, Davis S, et al. Stable chromosome aberrations and ionizing radiation in airline pilots. *Aviat Space Environ Med* 2003;74(9):953–958.
24. Durante M, George K, Wu H, et al. Karyotypes of human lymphocytes exposed to high-energy iron ions. *Radiat Res* 2002;158:581–590.
25. George K, Durante M, Willingham V, et al. Chromosome aberrations of clonal origin are present in astronauts' blood lymphocytes. *Cytogenet Genome Res* 2004;104:245–251.
26. ICRP Publication 92: Relative Biological Effectiveness, Quality Factor, and Radiation Weighting Factor, 92. Elsevier, 2003.
27. *IARC monographs on the evaluation of carcinogenic risks to humans*. Vol. 75. *Ionizing radiation, Part 1: X- and gamma radiation, and neutrons*. Lyon: International Agency for Research on Cancer, 2000.
28. American College of Radiology and The Radiological Society of North America–RadioInfo. www.radiologyinfo.org, accessed 22 July 2007.
29. Leibel SA, Phillips TL. *Textbook of radiation oncology*. Philadelphia: WB Saunders, 1998.
30. International Commission on Radiological Protection. *1990 Recommendations of the international commission for radiological protection*. New York: Elsevier Science, 1991.ICRP Publication 60; Annals of the ICRP21.
31. *Document of the national radiological protection board*. Chilton, Oxford: NRPB, 1993:4.
32. Federal Aviation Administration. *Crewmember training on in-flight radiation exposure*. Advisory circular 120–61, May 19, 1994.
33. Friedburg W, Copeland K. *What aircrews should know about their occupational exposure to ionizing radiation*. Washington, DC: Office of Aerospace Medicine, 2003. DOT/FAA/AM-03/16. 20591; October.
34. Friedberg W, Copeland K, Duke FE, et al. Radiation exposure of aircrews. *Occup Med State Art Rev* 2002;17(2):292–309.
35. European Communities. *The basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation*. Luxembourg: Office for Official Publications of the European Communities; 1996. Council Directive 9/29/EURATOM of 13 May 1996; *Official Journal of the European Communities* 1996; 39: L159.
36. Friedberg W, Faulkner DN, Snyder L, et al. Galactic cosmic radiation exposure and associated health risks for air carrier crew members. *Aviat Space Environ Med* 1989;60:1104–1108.
37. Preston DL, Shimizu Y, Pierce DA, et al. Studies of mortality of atomic bomb survivors. Report 13: solid cancer and noncancer disease mortality: 1950–1997. *Radiat Res* 2003;160:381–407.
38. Worgul BV, Kundiyev YI, Sergiyenko NM, et al. Cataracts among chernobyl clean-up workers: implications regarding permissible eye exposures. *Radiat Res* 2007;167:233–243.
39. Bagshaw M. Cosmic radiation measurements in airline service. *Radiat Prot Dosim* 1999;86(4):33–33.

40. Bagshaw M. British Airways measurement of cosmic radiation exposure on Concorde supersonic transport. *Health Phys* 2000;79(5):591–591.
41. Campbell RD, Bagshaw M. *Human performance and limitations in aviation*, 3rd ed. Oxford: BSP, 2003.
42. Davies DM. Cosmic radiation in Concorde operations and the impact of the new ICRP recommendations on commercial aviation. *Radiat Prot Dosim* 1993;51:121–124.
43. Preston FS. Eight years of Concorde operations: medical aspects. *J R Soc Med* 1985;78:193.
44. EURADOS Working Group 11. *The radiation exposure and monitoring of aircrew*. Luxembourg: European Commission Publication: Radiation Protection 85, 1996. Eurados Report 1996–01.
45. Kaji M, Fujitaka K, Sekiya T, et al. In-situ measurements of cosmic radiation dose equivalent on board aircraft to/from Japan: 2nd report. *Aviat Space Environ Med* 1995;66:517.
46. Lewis BJ, Bennett LG, Green AR, et al. Galactic and solar radiation exposure to aircrew during a solar cycle. *Radiat Prot Dosim* 2002;102(3):207–227.
47. Lindborg L, Karlberg J, Elfhag T. *Legislation and dose equivalents aboard domestic flights in Sweden*. Stockholm: Swedish Radiation Protection Institute, 1991. SSI Report 91–12.
48. Oksanen PJ. Estimated individual annual cosmic radiation doses for flight crews. *Aviat Space Environ Med* 1998;69:621–625.
49. Regulla D, David J. *Radiation measurements in civil aviation*. Germany: Institut fur Strahlenschutz, 1993. Final report GSF/BG/DLH research project.
50. Schumacher H, Schrewe UJ. *Dose equivalent measurements on board civil aircraft*. Radiation Protection Dosimetry, Oxford University Press, Braunschweig, Germany, 1993. Report PTB-Bericht N-13.
51. Spurny F, Dachev T. Measurement onboard an aircraft during an intense solar flare, ground level event 60, on April 15 2001. *Radiat Prot Dosim* 2001;95:273–275.
52. O'Brien K. *LUIN, a code for the calculation of cosmic ray propagation in the atmosphere*. New York: Environmental Measures Laboratory, 1978. EML-338.
53. Scraube H, Mares V, Roesler S, et al. Experimental verification and calculation of route doses. *Radiat Prot Dosim* 1999;86:309–315.
54. Roesler S, Heinrich W, Schraube H. Calculation of radiation fields in the atmosphere and comparison to experimental data. *Radiat Res* 1998;151:87–97.
55. Hosegood I. Occupational health issues in ultra-long range (ULR) airline operations. *Proceedings of IATA Cabin Health Conference*. Geneva, 2004.
56. Bagshaw M. Perspectives of those impacted. *Health Phys* 2000;79(5):608–609.
57. Beninson D, Dunster HI. *ICRP public statement*, London, 9 May, 1991.
58. Gundestrup M, Storm HH. Radiation-induced acute myeloid leukaemia and other cancers in commercial jet flight deck crew: a population-based cohort study. *Lancet* 1999;358:2029–2031.
59. Irvine D, Davies DM. British Airways flightdeck mortality study, 1951–1992. *Aviat Space Environ Med* 1999;70:591–559.
60. Blettner M, Zeeb H, Auvinen A, et al. Mortality from cancer and other causes among male cockpit crew in Europe. *Int J Cancer* 2003;106:951–958.
61. Zeeb H, Blettner M, Langner I, et al. Mortality from cancer and other causes among airline cabin attendants in Europe: a collaborative study in eight countries. *Am J Epidemiol* 2003;158:35–51.
62. Pukkala E, Aspholm R, Auvinen A, et al. Cancer incidence among 10, 211 airline pilots: a Nordic study. *Aviat Space Environ Med* 2003;74(7):699–706.
63. Rafnsson V, Sulem P, Tulinius H, et al. Breast cancer risk in airline cabin attendants: a nested case-control study in Iceland. *Occup Environ Med* 2003;60:807–809.
64. Rafnsson V, Tulinius H, Jonasson JG, et al. Risk of breast cancer in female flight attendants: a population-based study (Iceland). *Cancer Causes Control* 2001;12:95–101.
65. Rafnsson V, Olafsdottir E, Hrafnkelsson J, et al. Cosmic radiation increases the risk of nuclear cataract in airline pilots: a population-based case-control study. *Arch Ophthalmol* 2005;123:1102–1105.
66. Stern CH. Cataract surgery in pilots. *Aviat Space Environ Med* 2006;77(3):305–306.
67. National Academy of Sciences National Research Council. *Radiobiological factors in manned space flight*. Washington, DC, Publications 1487, 1967.
68. National Academy of Sciences National Research Council. *Radiation protection guides and constraints for space-mission and vehicle-design studies involving nuclear system*, Washington, DC, 1970.
69. National Council on Radiation Protection and Measurements, NCRP. *Guidance on radiation received in space activities. NCRP Report 98*. Bethesda, 1989.
70. National Council on Radiation Protection and Measurements. *Recommendations of dose limits for low earth orbit. NCRP Report 132*. Bethesda, 2000.
71. Cucinotta FA, Durante M. Cancer Risk from exposure to galactic cosmic rays: implications for space exploration by human beings. *Lancet Oncol* 2006;7:431–435.
72. Cucinotta FA, Schimmerling W, Wilson JW, et al. Space radiation cancer risks and uncertainties for mars missions. *Radiat Res* 2001;156:682–688.
73. National Council on Radiation Protection and Measurements, NCRP. *Uncertainties in fatal cancer risk estimates used in radiation protection. NCRP Report 126*, Bethesda, 1997.
74. Health Effects of Exposure to Low Levels of Ionizing Radiation, BEIR V. National Academy Press, Washington, D.C. 1990.
75. Benton EV. Summary of radiation dosimetry results on the u.s. and soviet manned spacecraft. *Adv Space Res* 1986;6:315–328.
76. Badhwar GD, Cucinotta FA. A comparison of depth dependence of dose and linear energy transfer spectra in aluminum and polyethylene. *Radiat Res* 2000;153:1–8.
77. Badhwar GD, Atwell W, Badavi FF, et al. Space radiation absorbed dose distribution in a human phantom. *Radiat Res* 2002;157:76–91.
78. Cucinotta FA, Wu H, Shavers MR, et al. Radiation dosimetry and biophysical models of space radiation effects. *Gravit Space Biol Bull* 2003;16(2):11–18.
79. Cucinotta FA, Kim MY, Ren L. Evaluating shielding effectiveness for reducing space radiation cancer risks. *Radiat Meas* 2006;41:1173–1185.

RECOMMENDED READINGS

Hendee WR, Edwards FM, eds. *Health effects of exposure to low-level ionizing radiation*. Bristol, Philadelphia: Institute of Physics Publishing, 1996. ISBN 0-7503-0349-2.

NCRP, National Council on Radiation Protection and Measurements. Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit. Report 153, Bethesda, MD (2006).

CHAPTER 9

Aerospace Toxicology and Microbiology

John T. James, A. J. Parmet, and Duane L. Pierson

> All substances are poisons: There is none which is not a poison. The right dose differentiates a poison and a remedy.
>
> Paracelsus (Philippus Aureolus Theophrastus Bombastus von Hohenheim, 1493–1541).

INTRODUCTION TO TOXICOLOGY

Toxicology dates to the very earliest history of humanity with various poisons and venom being recognized as a method of hunting or waging war with the earliest documentation in the Evers papyrus (circa 1500 BCE). The Greeks identified specific poisons such as hemlock, a method of state execution, and the Greek word *toxos* (*arrow*) became the root of our modern science. The first scientific approach to the understanding of poisons and toxicology was the work during the late middle ages of Paracelsus. He formulated what were then revolutionary views that a specific toxic agent or "toxicon" caused specific dose-related effects. His principles have established the basis of modern pharmacology and toxicology. In 1700, Bernardo Ramazzini published the book *De Morbis Artificum Diatriba* (The Diseases of Workers) describing specific illnesses associated with certain labor, particularly metal workers exposed to mercury, lead, arsenic, and rock dust. Modern toxicology dates from development of the modern industrial chemical processes, the earliest involving an analytic method for arsenic by Marsh in 1836. Industrial organic chemicals were synthesized in the late 1800s along with anesthetics and disinfectants (1). In 1908, Hamilton began the long study of occupational toxicology issues, and by World War I the scientific use of toxicants saw Haber creating war gases and defining time-dosage relationships that are used even now (2).

Aviation

The advent of aviation in World War I also saw the first use of toxins affecting pilots and ground crew. In particular, the use of castor oil as a lubricant required pilots in open cockpit aircraft to wear goggles for eye protection, and scarves around their mouths to reduce ingestion and inhalation, but the nauseating effects of this compound could not be avoided (3). Early ground support also involved hazardous chemicals causing "airplane dope poisoning" due to butyl acetate, ethyl acetate, and isopropyl alcohol inhalation (4). The modern industrial complex that supports aviation requires the use of complex and often dangerous chemicals and industrial processes, which can adversely affect the health of workers in the production, maintenance, and basic operations of an aircraft. The industrial base employs many times more people than are occupied as aircrew. Aircrew themselves may be exposed to toxicants in the course of routine operations, but are at greater risk during mishaps. The need to supply a portable form of energy to propel aircraft and spacecraft necessitates the use of high-energy fuels and hazardous oxidizers, which in the course of handling and use creates certain unique toxic hazards to the humans and the environment (5).

Space Flight

The conduct of space flight in sealed capsules and the use of reactive compounds for propulsion have caused toxicologic concerns from the earliest days of human space flight (6). Before the first Apollo moon landing, the National Academy of Sciences (NAS) released a long report recommending that submarine air quality standards for 90 days of continuous exposure be adopted for spacecraft, and that proposed limits for 60 minutes and 1,000 days of exposure be considered provisional for selected compounds (7). In 1972, the National Research Council (NRC) published limits on 52 compounds for exposure durations from 60 minutes to 6 months, with a few limits set for 10 minutes of exposure (8). The National Aeronautics and Space Administration (NASA) continued to set and revise its spacecraft maximum allowable concentrations (SMACs) independently of any outside expert panel; however, by 1989 it was apparent that the NRC should be engaged again to formally review and set air quality guidelines for the planned space station. Since then, NASA and the NRC have maintained a partnership to set and fully document exposure guidelines for air and water quality. Most recently, these limits are being extended once again to 1,000 days as planning begins for long-duration missions to the moon and Mars.

The Apollo 1 (originally numbered 204) fire in January 1967 on the pad at the Kennedy Space Center resulted in the death of three crewmembers in part due to toxic exposures to combustion products that were thought to include carbon monoxide, carbon dioxide, and irritant gases (9). A few years later, an Apollo crew was exposed to nitrogen tetroxide fumes as the capsule descended through the Earth's atmosphere after a successful low Earth orbit rendezvous with a Soyuz capsule in 1975 (10). Other dramatic events in the toxicologic history of space flight include the refrigerator motor failure aboard STS-40 in which copious amounts of formaldehyde were generated from pyrolyzed Delrin polymer (11); the solid fuel oxygen generator (SFOG) fire aboard Mir in 1997 that produced little carbon monoxide but did generate organic compounds including benzene; the pyrolysis event 1 year later in the microimpurity filter that produced hundreds of parts per million (ppm) of carbon monoxide and elicited delayed headache and nausea in the crew; the persistent leaks of ethylene glycol from the thermal loops of the Mir; and the ill-fated regeneration of the metal oxide canisters used during extravehicular activity aboard the International Space Station (ISS) that caused the crew to take refuge in the Russian segment of the ISS for 30 hours to avoid the noxious vapors from the canisters regenerated in the U.S. segment (12).

Toxicologic risks associated with space flight have been a challenge to manage because of the diversity of sources, the risks from pyrolysis of polymeric material, and the limited options available to deal with such events. Despite a concerted effort toward space flight safety, it is reasonable to anticipate that such events will continue to occur as we endeavor to fly a complex ISS with an expanded number of crew, fly sorties and long-duration flights to the moon, and begin Mars exploration by humans.

BASIC PRINCIPLES OF TOXICOLOGY

Potency

A poison may be defined as an agent capable of producing an adverse effect. Virtually every chemical, including water, can produce an adverse effect in sufficient amounts. Toxic agents can be classified by the potency or relative dose required to elicit a specific adverse effect. This creates a spectrum of poisons with potencies differing by many orders of magnitude. A relative degree of toxicity can be expressed by comparing lethal doses (LDs) in six categories. For example, supertoxic agents require a dose of less than 5 mg/kg of body mass to produce death in half of those exposed, a concept expressed as the LD_{50}. Examples of supertoxic chemicals are botulism toxin and nicotine. An extremely toxic poison requires between 5 and 10 mg/kg for an LD_{50}, for example, the organophosphate pesticide malathion. A very toxic chemical has an LD_{50} from 50 to 500 mg/kg, with an example being phenobarbital. A moderately toxic agent has an LD_{50} in the 500 to 5,000 mg/kg range. An example would be table salt, sodium chloride. A slightly toxic chemical with an LD_{50} of 5,000 to 15,000 mg/kg is ethyl alcohol. A nontoxic agent, such as water, requires more than 15,000 mg/kg to produce an LD_{50} (13).

Route of Exposure and Target Organs

Except for contact toxicants, the initial step in exposure is absorption, which is the process by which a toxicant enters the body. Absorption can occur through various pathways. Inhalation is the most common pathway seen in the aerospace environment with vapors (gaseous component), fumes (oxides of metals), and solid particles entering the respiratory system. Water solubility determines the depth of penetration into the respiratory system. The highly soluble gas, sulphur dioxide (SO_2), is readily absorbed in the nose, whereas the poorly soluble gas, nitrogen dioxide (NO_2), penetrates deeply into the lung where serious injury can ensue. For fumes and dust particles, aerodynamic size determines the depth of penetration. Under conditions of nasal breathing, particles larger than 5 μm are typically captured in the nasopharyngeal region, those in the size range of 1 to 5 μm in the tracheobronchial region, and those less than 1 μm in the alveolar region. These particles may be removed from the lungs by the mucociliary escalator, by dissolution, or by the lymphatic drainage system. Smaller particles may penetrate to the alveoli and will be absorbed through epithelial membranes into the body (14). Special forms of particles, such as fibers (asbestos, carbon fibers), are measured by their cross section so that a long, hair-like particle traveling lengthwise acts like a small particle based on its cross sectional area and not on its length.

Chemicals enter the body through routes other than the pulmonary system. The eyes and nasal mucosa are nonkeratinized epithelium and readily absorb water-soluble particles and respond to acids and bases. The skin, however, is waterproof and lipid proof, and highly resistant to absorption of most chemicals. Only chemicals with unique polarity, such as dimethyl sulfoxide, can penetrate intact skin, although burns and infections may break down the keratinized layer and permit significantly increased amounts of chemicals to cross the dermal barrier and enter the body. Ingestion through the gastrointestinal tract provides opportunities for chemicals requiring acidic environments (the stomach) or alkaline environments (esophagus and duodenum) to be solubilized and absorbed. Finally, some chemicals may be injected intentionally across the skin in a parenteral manner through accidents or medical procedures.

The next phase of exposure is called *distribution*. Chemicals will be dispersed throughout the body, often redistributing on the basis of their pH-based solubility or solubility in fat. Those chemicals that tend to dissociate in an acid environment such as aspirin will concentrate in low pH areas such as the stomach or joint spaces even when absorbed by another mechanism. Therefore, aspirin taken as an enteric-coated capsule and absorbed in the small intestine will eventually distribute back into the stomach. Other chemicals will distribute by the nature of their binding capacity for blood proteins, especially albumin. Protein-bound toxicants are not available to disperse into other tissues until they have been freed by dissociation. Metals such as lead will be carried on specific proteins designed as carriers for normal metabolic components. In the case of lead, erythrocyte protoporphyrin, normally used to transport zinc, will carry the chemically similar lead where it will bind in place of zinc and calcium.

Once in the body, chemicals are distributed and will contact the target organ. Highly perfused organs (e.g., liver) will receive more of a toxicant than those less perfused. Special transport proteins concentrate selected toxicants into certain organs; for example, iodine is concentrated into the thyroid by a protein in thyroid cell membranes. Most toxicants have a specific binding site where the effect takes place. For lead, it may substitute for zinc in intracellular processes affecting the synthesis of heme or it may substitute for calcium in bone. Other chemicals, particularly strong acids or alkalies such as hydrazine, are nonspecific, and their effects are to denature proteins of all kinds causing a very nonspecific response at the binding site.

Metabolism will also affect the outcome of chemical exposure. Enzymes in the nasal mucosa and stomach will often metabolize chemicals before they enter the body. Gastric dehydrogenases break down ethyl alcohol within the stomach, and differing amounts of the enzyme such as larger amounts present in males than females, will affect the relative toxicity. Chemicals absorbed through the gastrointestinal tract undergo first-pass metabolism in the liver through the portal system. Therefore, chemicals absorbed from the stomach and intestine will travel to the liver before entering the general distribution. The importance of metabolism is illustrated in this example: cocaine ingested in the form of tea, commonly done in South America, is metabolized to benzylecgonine, a nonpsychoactive agent, and therefore very little of cocaine taken as an ingested liquid enters the system and causes psychogenic effects. When cocaine enters the body through lungs or nasal mucosa, this first-pass metabolism is not present and no transformation of the chemical and psychotic effects are observed (15). Biotransformation may also adversely change a chemical, as demonstrated by aflatoxin, which is transformed by cytochrome P-450 in the liver into a carcinogen through its first-pass metabolism (16).

Ultimately, a toxicant will be eliminated through any one of a number of excretion systems. Many chemicals are excreted through the kidneys into urine. Others may be excreted through the bile, although these toxicants may be subject to enterohepatic recirculation. An example is mercury, which is excreted in the bile by methylation in the liver. However, in the colon, intestinal bacteria will break down the methyl mercury and allow reabsorption and return to the system (17). This can prolong the effective half-life of the chemical. Other chemicals such as solvents can be excreted as vapor through the lungs, an example being ethyl alcohol. Ethanol itself, being a carbohydrate, is also metabolized to acetaldehyde, acetic acid, and carbon dioxide. Other chemicals may be excreted as deposits in the hair, skin, and nails. Examples are arsenic and cannabinoids. Some chemicals may be stored for long periods of time, particularly those soluble in fats or in bone. All these reservoirs can serve to affect the half-life of a chemical in the body and can possibly lead to toxicity if the reservoir is suddenly "emptied." For example, as bone is mobilized during space flight, the release of other compounds stored in bone, such as lead, could cause toxicity if the amount stored in bone were sufficiently high before flight (18).

Extrapolations in Exposure Times and Species

Judgments must be made concerning the dose that a human can take without succumbing to toxicologic effects. Those judgments are formed *a priori* and given as exposure standards for specific times of exposure to avoid specific adverse effects. The data to set such standards is often in a nonhuman species and has not been generated for the times of exposure for which a standard is needed. To set the human exposure standard, a paradigm for extrapolation from one species to another is needed and another paradigm is needed to extrapolate from one time of exposure to another. There is by no means a consensus on how each of these extrapolations should be done. Some of the options are discussed in the subsequent text.

The most accurate method for extrapolation of animal data to the human condition is through physiologically based pharmacokinetic (PBPK) modeling. By this approach, the concentration of the ultimate toxicant (the one causing the injury) is modeled and measured where possible to estimate the differences between the tested species and the human. Physiological and metabolic parameters must be derived or assumed for each species in this approach, and the modeling must account for changing routes of metabolism as the exposure concentration increases and metabolic pathways are overwhelmed. For example, a PBPK model has been used to compare the relative blood concentrations of *n*-butanol (a common spacecraft pollutant) in rats and make a prediction in humans if they were exposed to a precursor of the alcohol (*n*-butyl acetate) (19). The target endpoint to be avoided is central nervous system depression, which can be observed in the exposed rats as reduced voluntary activity.

When extrapolating from one species to another, the toxicologist must ask whether the toxic effect observed in the animal species is relevant to human exposures. Examples where rodents are an inappropriate model for humans include the calcium mobilization response of guinea pigs to elevated carbon dioxide, the neoplastic response of rats to thyroid carcinogens, and the hyaline-droplet accumulation in the male rat kidney during solvent exposures (20). Another example of an inappropriate endpoint is the neoplastic response of rat liver to ingestion of di (2-ethylhexyl) phthalate in water. Rodents absorb much less of the toxicant than humans after ingestion, but the peroxisome proliferative response in their livers, which is mediated by peroxisome proliferator–activated receptor-α, is nearly absent in primates (21). The toxicologist must consistently question the relevance of the modeled response to a toxicant and the expected human response.

Low-dose Extrapolation

One of the classic problems in toxicology is extrapolation of the toxic responses of an animal model at high doses to the anticipated response at much lower doses, well below any of those used in the animal study. The typical approach to this problem is to derive a dose–response curve that expresses the severity or incidence of a response to toxicant exposures. In the last decade, the benchmark dose approach has been promulgated by the NRC and others as a means of estimating low-dose responses from studies performed at higher doses (22). As the Johnson Space Center (JSC) Toxicology Group has attempted to apply this method to setting of exposure guidelines in cooperation with the NRC, three issues with its application have emerged. The first problem is the random variability in the data when the number of test animals per dose is in the vicinity of 10, which is a typical number for many studies. The second problem is how to select the model or models to fit the data, and then how to combine their predictions into a single parameter. The third problem is which statistical endpoint to use as the predictor. Should it be the lower confidence limit or the maximum likelihood value, and should the predicted risk level be 1%, 5%, or 10%? There is not a consensus on how benchmark dosing should be applied; however, it is deemed to be an improvement on the default approach of using a no-observed-adverse-effect level as a starting place for low-dose predictions.

Combined Exposures

In any actual situation, people are exposed to mixtures of compounds in the air and water. Often the toxic risk is primarily due to a single pollutant; however, at other times the combined effects of several compounds must be considered. For example, the initial step to addressing the problem of multiple-compound exposures is to calculate a toxicity index (T value) for each space mission. The calculation is as follows:

$$\text{T value} = \sum_{i=1}^{n} C_i/SMAC_i$$

Where there are "n" compounds found at concentrations C_i and the exposure standard for the i^{th} compound is the $SMAC_i$, which is the limit for the time the crew has been exposed. For example, for short Shuttle missions the 7-day SMACs are typically used, whereas for a prolonged stay aboard the ISS, the 180-day SMACs are used. The air is considered acceptable if T is less than 1; however, this is often not the case. When T greater than 1 is found, the compounds are sorted into groups according to their toxic mechanism or target organ. For example, irritants, carcinogens, hematotoxicants, immunotoxicants, neurotoxicants, cardiotoxicants, and so on constitute separate groups. Then a T_{group} is calculated for each group of toxicants. The air is considered safe if each T_{group} is less than 1 unit. Note that some compounds with multiple toxic effects, such as carbon monoxide, can contribute to more than one group. To apply this method, one must know *a priori* the target organs of each compound, and that is sometimes not well established.

Immediate versus Delayed Toxic Effects

It is important that flight surgeons and biomedical engineers supporting a flight be aware that certain toxicants do not elicit their maximum effects immediately, or the nature of the effect may change with time. A good example of this is the delayed pulmonary edema caused by nitrogen tetroxide exposures in the Apollo capsule as the oxidizer was aspirated into the capsule from thrusters. The estimated time of exposure was 4 minutes and 40 seconds at an average concentration of 250 ppm, with a peak at 700 ppm. One crewmember was unconscious when the capsule was opened. The crew experienced immediate symptoms of respiratory irritation, but the pulmonary edema (infiltrate) was delayed for about a day (10). The symptoms included chest tightness, a retrosternal burning sensation, and a cough upon deep breathing. Chest x-rays taken the following day were suggestive of chemical pneumonitis; however, these findings returned to normal 5 days after landing. The crew was treated with oral steroids. To our knowledge, no long-term health consequences have been reported in the three crewmembers.

Another example of delayed toxic effects during space flight was the carbon monoxide exposure after the microimpurity filter pyrolysis aboard Mir. When crewmembers were exposed to several hundred ppm of carbon monoxide, several hours were required for the carboxyhemoglobin to accumulate in the blood to its maximum level. Therefore, it was not until approximately 8 hours after their initial exposure that any crewmembers reported headache and nausea after the filter burn.

Adaptive Responses versus Adverse Effects

When assessing the health significance of a toxic exposure, one must clearly delineate *adaptive responses* of an organism from *adverse effects* caused by a toxicant. One example that directly applies to space flight is the anthropogenic compound carbon dioxide (CO_2). The normal outdoor concentration of carbon dioxide is approximately 0.05%; therefore, it is relatively easy for people to discharge this metabolic product from the body. Hyperventilation (an adaptive response) can be demonstrated at exposure concentrations of 1% or more, but the effect goes unnoticed by the person exposed. The increased respiratory rate is mediated by chemoreceptors in the carotid and brain; however, if the exposure is prolonged, it appears that the hyperventilation fades as the person acclimates to the high CO_2 during weeks of exposure (see Chapter 2). Substantially higher concentrations (>3%) are generally required to elicit clearly adverse effects such as headaches, dyspnea, or intercostal pain (23). Spacecraft are operated to maintain the concentration below 0.7% (7,000 ppm), but there may be sensitive crewmembers who are susceptible to headaches even at this low concentration.

Individual Sensitivities (Genetic Factors)

Individuals can vary in their response to toxic insult because of age, health status, previous exposure, or genetic differences. People who are very young or very old are generally considered to be more susceptible to environmental toxicants. Persons with respiratory disease are likewise more susceptible to air pollutants and are often warned to remain inside when air quality in urban areas is poor. Previous exposures can either increase a person's sensitivity to subsequent exposure or decrease it. In occupational asthma and reactive airways disease, once an allergen has sensitized an individual, subsequent reexposure will evoke a symptomatic response at a much lower level (24). On the other hand, smokers, human test subjects, and even experimental animals that experience multiple exposures to carbon monoxide have adapted to it, and are therefore less susceptible to some of the adverse effects of carbon monoxide than naïve organisms (25).

Our understanding of the genetic basis for differences in susceptibility of individuals to toxic insults is being revolutionized by the new field of toxicogenomics, which is the study of all genes of a cell or tissue at the DNA, messenger ribonucleic acid (mRNA), or protein level (26). Before the era of toxicogenomics, there had been long-standing recognition that certain persons were much more susceptible to adverse effects when exposed to certain toxicants. An example that applies to aviation and to space flight is that of ethanol. Ingestion of ethanol is discouraged in both settings, yet we must recognize that certain individuals are extremely prone to the "alcohol sensitivity syndrome," because of genetic polymorphisms in the enzymes that catalyze the removal of ethanol's metabolite, acetaldehyde. In sensitive individuals, this compound causes an unpleasant flushing response, which includes facial redness, increased pulse rate, headache, nausea, and drowsiness, even with a single ingestion of a small amount of ethanol (27). Toxicogenomics facilitates our understanding at the molecular level of the effect of a toxicant on the genome as well as our understanding of individual variability in susceptibility because of their genetic predisposition to be adversely affected by exposure to a compound. In principle, each person could be screened for genetic markers that suggest their level of susceptibility to the adverse effects of a drug or toxicant.

SPECIFIC CHEMICALS IN THE AEROSPACE ENVIRONMENT

Aviation Fuels and Compounds

Liquid aviation fuels are primarily petroleum-based compounds. In general, all aviation propellants consist of mixtures of alkanes, cycloalkanes, and other hydrocarbons in varying ratios. All are volatile and flammable. Petroleum-based fuels fall into two categories: aviation gasoline or jet fuel. In most locations across the globe, aviation gasoline or avgas no longer contains tetraethyl lead, which was removed for environmental protection. Most jet fuel is a blend of kerosene with specific additives to produce characteristic performance. Each manufacturer of avgas and jet fuel will blend approximately 300 hydrocarbon compounds to produce the energy requirements, controlled oxidation, and inhibition of corrosion and freezing necessary for specific applications. Blends are adjusted for seasonal changes in weather and to control "weathering" of stored fuels in specific locations (5).

Fuels can cause skin irritation, and the vapors will cause nausea and sedation. Long-term inhalation can lead to neuropathies and are suspect for hepatotoxicity and carcinogenicity (28). However, most fuels are now handled by a single-point system. This means that the fuel line must be locked and sealed between the tankers and aircraft so that no fuel will flow until the system is closed. This produces very minimal exposure to fuel vapors in the occupational setting (29). Combustion products of fuels include carbon monoxide, carbon dioxide, incompletely oxidized hydrocarbons, and oxides of nitrogen generated by heating of atmospheric nitrogen. The exhaust of internal combustion engines using aviation gas tend to be rich in carbon monoxide whereas jet fuel burning gas turbine engines are typically low in carbon monoxide, but may be high in oxides of nitrogen.

Other petroleum products encountered in the aviation environment include lubricants, which are typically heavier oils and hydraulic fluids. Some hydraulic fluids have phosphate components, and under certain circumstances such as combustion highly toxic organophosphates may be generated. Despite this concern, there is no consistent proof that such events have occurred; nonetheless, such fluids have generally had the phosphate esters substituted (30). Deicing fluids may contain ethylene glycol or propylene glycol, which have the potential to be nephrotoxic and must be recovered to prevent environmental contamination (31).

Rocket Fuels

Rocket fuels may consist of kerosene (RP1) used in the Atlas missile, liquid hydrogen which is used for the main engines of the space shuttle and upper stages of other missiles, or hydrazine (32). The toxicologic properties of kerosene are similar to jet fuels. Hydrogen is a nontoxic gas that is a cryogenic liquid at −255°C. Hydrazines are used as the fuel in hypergolic engines. This fuel when mixed with an oxidizer will spontaneously combust. Hydrazines are available as hydrazine ($H_2N\text{-}NH_2$), monomethyl hydrazine (MMH) ($H_2N\text{-}NHCH_3$), and unsymmetrical dimethyl hydrazine (UDMH) ($H_2N\text{-}N(CH_3)_2$). Hydrazines are used as the fuel for the space shuttle orbiter maneuvering system and reaction control systems and as the power supply for the auxiliary power unit on F-16 fighters. In the F-16, MMH is passed through a catalytic converter, which decomposes hydrazine to ammonia and steam (33). Hydrazines are very stable, clear, and colorless liquids with an ammonia-like odor. However, hydrazine is much more toxic than ammonia. Ammonia has a 24-hour SMAC of 20 ppm and can be smelled at 5 ppm, whereas hydrazine is also smelled at 5 ppm, but its 24-hour SMAC is only 0.3 ppm (NASA/JSC 20584, March 2001). As highly alkaline chemicals, they rapidly penetrate intact skin and coagulate proteins. Extreme toxicity to the eyes and respiratory tract occur, and workers should have complete isolation in the form of respiratory and skin protection. Rapid decontamination with copious amounts of water is necessary, followed by symptomatic treatment of skin, eye, and airway injury. Seizures may occur following MMH absorbtion and are resistant to standard therapy. Pyroxidine treatment at 25 mg/kg has been suggested from experimental studies (34).

Nitrogen tetroxide and nitric acid are the oxidizer components in hypergolic engines and spontaneously ignite when mixed with hydrazines. These oxidizers are used in the space shuttle onboard maneuvering system as well as the upper stage for other rocket engines (35). They are highly acidic, forming nitric acid on contact with water or the human body, and will rapidly cause burns to the eyes, skin, and respiratory tract. Complete protection must occur if these oxidizers are present in the environment. Rapid decontamination with copious amounts of water is necessary, followed by symptomatic treatment of skin, eye, and airway injury. Inhalation injury may include pulmonary edema, which may be fatal or result in residual bronchiolitis obliterans (36)

Solid fuels contain a mixture of ammonium perchlorate, the oxidizer, and a metal, usually aluminum or magnesium, which is the fuel. Additionally, a binding agent such as a plastic will be included in the mixture to create a stable solid. Most air-to-air missiles and the solid rocket boosters for space shuttle use this composition. This mixture is extremely stable until ignited and the combustion products produced are hydrochloric acid and a metal oxide (37). The exhaust gases are irritating to eyes and the respiratory tract (38).

Toxic Space Systems Chemicals

Ammonia

This water-soluble gas accumulates slowly in spacecraft atmospheres because of human metabolism, but it is effectively removed by filters and by cocondensation with water into the humidity condensate. Other sources of ammonia contamination on the ISS include external and internal thermal loops. Anhydrous ammonia, used in the external thermal loop of the U.S. segment of the ISS, presents a small risk of suit contamination when the loop is serviced. In addition, there is a remote risk of ammonia penetrating into the inner thermal loops, and subsequently into the ISS internal environment. Flight rules, based on data from ammonia monitoring devices, have been formulated to manage ammonia present in the airlock after an extra-vehicular activity (EVA), and to manage a potentially catastrophic leak into the ISS from the thermal loops. The primary toxic effect of ammonia is respiratory system and eye irritation but formation of ammonium hydroxide in tissues from exposure to high concentrations of ammonia can lead to alkali-like chemical burns. Typically, ammonia can be smelled before harmful exposures occur; however, adaptation to slow increases in its concentration could result in undetected higher exposures (39).

Glycols

When mixed with water, glycols make good heat-exchange fluids. An ethylene glycol solution was used on Mir as the heat exchanger, and this has been replaced in ISS with a fluid called *triol*, a mixture of glycerol and water. These fluids typically require trace amounts of anticorrosion and antimicrobial compounds that do not contribute significantly to the toxicity risk. Ethylene glycol vapor or fine aerosol can cause immediate irritation of mucosal surfaces, whereas ingestion of the liquid results primarily in intoxication and renal damage (40). The primary experience with this glycol was aboard the Mir space station in the late 1990s when frequent leaks from the thermal exchange system occurred. Because of the low volatility of the fluid, the airborne concentrations remained highest in the module where the initial leak occurred. The vapor spread into other modules over a period of weeks, but adjacent modules never reached as high a contamination level as the module where the leak first occurred based on the information acquired from the tracking of a single event with available analytic measurements. Exposed crewmembers reported mild mucosal irritation, and there were anecdotal reports of unpleasant encounters with floating "blebs" of the coolant fluid that resulted in moderate eye irritation. In contrast to ethylene glycol, the glycerol solution used in the Russian segments of the ISS is much less toxic. Furthermore, after 7 years of ISS operation, no fluid leaks have been detected.

Freons

This class of compounds also makes excellent heat-exchange fluids. Freon 21 and Fluorinert are used in the space shuttle, Freon 218 is used in the Russian air conditioner in the ISS service module, and various Freons have been proposed for use in payload experiments. Of the Freons used during space flight, Freon 21 is the most toxic with a 180-day exposure limit of only 2 ppm because of hepatotoxicity. Freon 218 is essentially devoid of toxicity, and its release into the ISS is of no toxicologic consequence. There are two important questions when assessing the toxicity of a

Freon: (i) Are there impurities in the as-used formulation that could be highly toxic, and (ii) can any compounds in the Freon be decomposed within a spacecraft environmental control system to a more toxic compound? Answering either of these questions can present a challenge because of proprietary issues and because the precise behavior of the compound inside an environmental control system is seldom well characterized.

Fire Extinguishants

There are three major classes of fire extinguishants that have been used aboard spacecraft in recent years: aqueous-based foams, carbon dioxide, and Halon (41–43). The first type is the kind that was used in an attempt to extinguish the SFOG fire aboard Mir in 1997. The result was that the fire persisted because of the oxygen being generated and the aqueous base became a fine aerosol of corrosive droplets (based on the appearance of air samplers returned after the incident). The current fire extinguishant used in the Russian segment of the ISS is similar in composition. Carbon dioxide is the extinguishant available in the U.S. segment of the ISS. There is some concern that the use of this in large quantities could increase the ambient carbon dioxide levels to potentially toxic levels and overwhelm the scrubbing capability. A supplemental carbon dioxide scrubber based on lithium hydroxide beds is flown aboard the ISS to deal specifically with excess carbon dioxide. Halon ($CBrF_3$) is used as the extinguishant aboard the Shuttle. This material is highly effective and low in toxicity. However, in the past some concerns have been voiced about thermal decomposition products if these were to be used. In a modest fire this would not be an issue, but in a large hot fire, hydrogen bromide (HBr) and hydrogen fluoride (HF) products could be produced in significant quantities. For example, Halon would not be an appropriate extinguishant to use on an SFOG fire.

Volatile Organic Compounds

Under nominal conditions, the major trace pollutants are organic compounds such as alcohols, ketones, aldehydes, and aromatics. The most toxic of the alcohols is methanol, which is seldom measured at concentrations above 1 ppm, but is generally present above 0.1 ppm. This compound can cause visual disturbances if long-term (months) exposures exceed 7 ppm (44). The most noxious of the small alcohols is *n*-butanol, which is typically present at approximately 0.1 ppm or less, but during the Metox regeneration contingency was found at concentrations up to 2.5 ppm (T value = 0.19) (12). The most toxic aldehyde is formaldehyde, which can cause mucosal irritation at concentrations well below 1 ppm. In fact, the 7- to 180-day limit for this compound was 0.04 ppm until it was recently increased to 0.1 ppm based on reevaluation of irritancy data (45). Under conditions of reduced intermodular ventilation in the ISS, it had been a challenge to maintain formaldehyde concentrations below 0.04 ppm; however, the higher standard can readily be met. The only aromatic compound that presents a significant toxicity risk on the ISS is benzene, which is a well-known immunotoxicant and carcinogen. Normally, this compound is below detection limits in air samples but it is occasionally generated during an accident [e.g., SFOG fire or Elektron (see Chapter 2)] from overheating and briefly reaches concentrations of a few ppm. Other aromatic compounds, such as toluene, and xylenes are consistently present in spacecraft air at harmless concentrations.

Toxic Fires and Other Unpredictable Toxic Sources in Spacecraft

Carbon Monoxide

CO is the most ubiquitous toxicant in most combustion or pyrolysis processes. CO is rapidly absorbed by inhalation and bonds to hemoglobin at a much higher rate than oxygen. Caution should be used in monitoring oxygen levels through pulse oximeters because these devices will measure carboxyhemoglobin and report it as oxygenated hemoglobin. Cyanide should always be suspected in any carbon monoxide exposure (46). Carbon monoxide is expected to significantly increase during ordinary combustion events that occur in space. Because convection does not occur to any significant extent in near-zero gravity, a small fire can quickly become oxygen depleted and thereby produce more CO than would be produced in an identical fire on Earth. The accidental burn within the regenerable microimpurity filtering system aboard Mir in 1998 demonstrated that a toxic exposure to CO can be produced from what appeared to be a minor event. Detector tubes and an electrochemical sensor are flown aboard ISS to help manage CO in the event of a fire. Moreover, an electrochemical sensor is available on Shuttle and an ambient temperature catalytic oxidizer filter is available to remove excess CO. For treatment of CO exposure see Chapter 2.

Acid Gases

When polymeric materials are subjected to thermal degradation, a "soup" of compounds is produced. Of the compounds in that mixture, the acid gases are expected to be the most hazardous based on the inherent toxicity of this class of compounds and the relative amounts expected in a fire. The compounds of most concern are hydrogen chloride (HCl), hydrogen cyanide (HCN), and HF. These originate from polymeric materials containing chlorine, nitrogen, or fluorine, respectively. Typical wiring insulation used in U.S. spacecraft consists of Kapton (a nitrogenous polymer) and Teflon (a fluorine-containing polymer). The short-term exposure limits for acid gases are in the few-ppm range because of the ability to irritate mucosal surfaces (HCl and HF) or cause depression of the central nervous system (HCN). U.S. crews are provided with an instrument capable of quantifying HCN and HCl; however, an accurate sensor for HF has proved elusive. More information on the toxicity of these compounds and monitoring strategies can be found on the JSC Toxicology Group website: http://hefd.jsc.nasa.gov/tox.htm.

Exposure Standards for Spacecraft Air Quality

Setting defensible exposure standards requires a broad range of expertise that cannot be found in single individuals. Therefore, such standards are typically set by a panel of experts selected for their knowledge of toxic effects, metabolism, epidemiology, statistics, pathology, and exposure methods. Since the earliest days of human space flight, with some gaps, the NRC Committee on Toxicology has provided a subcommittee with the needed expertise to advise NASA on appropriate environmental standards and documentation. According to the current paradigm, NASA toxicologists prepare a document for each compound containing a survey of the literature and how the data from that survey can be used to set exposure standards. After careful review, in an iterative process, adjustments are made to the document and proposed standards until all parties are satisfied that the approach and standards are defensible. The resulting documents and standards can be accessed through the website of the NRC (http://newton.nap.edu/books/NI000062/html/R15.html or http://www.nap.edu/books/0309091667/html) or through the JSC Toxicology Group website.

Federal Aviation Administration Standards for Air Quality in Commercial Aircraft

Cabin "altitude" is currently regulated to a maximum of 8,000 ft in commercial airliners. Carbon dioxide levels are recommended not to exceed 1,500 ppm by the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) Cabin Air Quality Technical Committee (47). The reason for this limit is not based on carbon dioxide physiology, which does not measurably change until levels of 3,000 ppm (3%) are exceeded (48). Instead, the 1,500-ppm standard is used to signify static air and potential for unpleasant aromas. In the commercial aircraft cabin, with many sources of carbon dioxide from human respiration and carbonated beverages, this has proved to be a difficult limit to meet. Control of trace gases in aircraft cabins to ensure the comfort of passengers and crew has been debated for decades. Disallowing smoking on such aircraft has greatly reduced the impetus for specifying levels of air pollution beyond the ones given in the preceding text; however, ASHRAE has had a draft set of standards out for review and the review period has closed. Recommended air quality standards may soon be available for commercial aircraft.

DUST

Dust Originating within the Spacecraft or Habitat

Floating particulate matter continues to be an issue for spacecraft operations and crew health. For example, flight rules now require that a crewmember must wear eye and respiratory protection when entering a new module attached to the ISS. This rule was developed because the debris that settled during ground preparations of the module floats once it reaches zero gravity. Other dust is not nearly so innocuous. For example, lithium hydroxide dust can escape from Shuttle CO_2 scrubbing canisters and may come in contact with the eyes potentially causing lasting damage to the cornea due to its corrosive nature. Recently, there has been concern about cadmium (Cd) dust in the ISS originating from corroded bayonet pins that were plated with Cd. After lengthy analyses and inspections of the pins and ISS air filters, it was concluded that any crew exposures to Cd dust were well below toxic levels.

External Sources of Toxic Dust in Celestial Habitats

During the Apollo missions, it was obvious that lunar dust could be a problem for the crew (49). This dust adhered tenaciously to surfaces such as spacesuits and accumulated in the Lunar Lander in large quantities. When the vehicle reentered the microgravity environment during lunar rendezvous, the dust floated into the air and at times presented a challenge for the crew to manage. Although there were several reports of the crew being annoyed by the dust, there was no unequivocal evidence that it was toxic. Exposures were brief and the crewmembers often replaced their helmets when the airborne dust was at its worst. When humans return to the moon's surface for long stays and surface vehicles are used for exploration, the potential for lunar dust to affect crew health is a concern. The processes that activate the surface of lunar dust particles and give it a large surface area (Swiss-cheese appearance) are unique to the moon, and it is possible that this reactivity and huge surface area could render the dust much more toxic than comparable Earth analogs (50). Efforts are under way to understand and mimic the activation processes found on the lunar surface, and determine how much these processes increase the toxicity of lunar dust. This problem is made more interesting and challenging because there are various types of dust, highland, mare, mature, and immature, to include in this endeavor.

PURGE GAS "TOXICITY"

Even gases that are viewed as totally nontoxic can be lethal if they are present in sufficient concentrations to displace oxygen. Coolants and purge agents come to mind in this regard. Nitrogen and helium are often used to create an inert environment over a fuel. These gases may be used to pressurize a fuel tank or to prevent air from entering the tank resulting in a fuel tank explosion. The presence of air inside the main fuel tank of an airliner can lead to catastrophic results such as the fuel tank explosion that destroyed TWA Flight 800 in 1996 (51). In that case, only a small amount of fuel remained in the main tank of the aircraft, allowing the upper explosive limit to be reached. New regulations requiring nitrogen pressurization in aircraft fuel tanks can prevent such an event in the future and were ordered by the Federal Aviation Administration (FAA) in 2007. Nitrogen-pressurized fuel tanks have been common practice in military transports for many years. The problem with the use of nitrogen or helium is the displacement of oxygen; if an individual enters the confined space, asphyxiation will result.

The mechanism of asphyxiation unfolds rapidly when an individual enters a closed environment where there is little oxygen; loss of consciousness occurs within 10 to 15 seconds. This situation unfolds rapidly because the diffusion gradient within the lung is reversed. Pulmonary arterial blood with an approximate PO_2 of 40 mm Hg typically is carrying less oxygen than the alveoli, which typically have a PO_2 of 100 mm Hg. However, in the presence of a pure nitrogen or helium atmosphere, the alveolar oxygen content would be 0, and oxygen would diffuse *from* the blood stream into the alveoli, resulting in virtually no oxygen being available in pulmonary venous blood, and within seconds the brain will have exhausted its reserves (52). These accidents may occur when workers enter fuel tanks that have been purged of fuel using an inert gas. Such an accident occurred on March 19, 1981 at the Kennedy Space Center when the Space Shuttle Columbia was being processed and a compartment had been purged with nitrogen gas. Two workers entered the compartment and rapidly lost consciousness. Five rescuers also lost consciousness and were themselves not rescued until other workers had donned self-contained breathing apparatus and were able to extract the rescuers, but the original two victims died (53).

DRUG AND ALCOHOL TOXICOLOGY

Aircrew and safety-sensitive personnel must comply with drug and alcohol rules of the United States Department of Transportation and the FAA in the United States and the Joint Aviation Administration in Europe. These rules are very similar and prohibit the use of alcohol at work and the use of banned drugs at work or at any other time. Drug testing is articulated in the Omnibus Transportation Employee Testing Act of 1991 and implemented by the FAA's own regulations. Drug testing is performed preemployment and after accidents as well as for reasonable suspicion and on a random basis. These are governed by Department of Transportation 49 CFR Part 40 and FAA 14 CFR with parts governing each section of flight operations. Safety-sensitive positions include flight crew, flight attendants, mechanics, aircraft dispatchers, ground security, flight instruction, air traffic control, and security personnel. The FAA and agency rules govern urine testing for specifically banned substances, which include amphetamines, opiates (morphine, codeine, and heroin but not semisynthetic opiates), phencyclidine, marijuana (cannabinoids), and cocaine.

Alcohol use is banned on duty. The FAA limits specifically ban the performance of safety-sensitive duties if alcohol is detected by an evidential breath alcohol tester (EBAT) at an equivalent blood alcohol concentration of 0.040%. Levels at or above this value are considered positive. Alcohol concentrations between 0.020% and 0.039% are not considered positive, but individuals must be removed from safety-sensitive functions for at least 8 hours and retested and found to have a level below 0.020%. Levels below 0.020% are considered negative and represent the lowest reasonable level that can be tested with accuracy.

Unlike pilots and other safety-sensitive commercial airline personnel, astronauts are not tested for alcohol use immediately pre-flight. In 2007, NASA chartered an astronaut health care system review committee; in the committee report it was stated that on at least two occasions "astronauts had been so intoxicated before flight that flight surgeons and/or fellow astronauts raised concerns to local on-scene leadership regarding flight safety (54)." From this observation, the NASA external review committee formulated recommendations. These can be summarized as follows: (i) policies, educational efforts, and discipline must target individual and supervisory accountability for responsible use of alcohol, (ii) an alcohol-free period must be established before flight, and (iii) a mechanism must be available to address concerns raised by responsible persons. A subsequent NASA survey could not substantiate the committee's observation of alcohol use by astronauts (55); however, NASA formulated a response to the review committee's report in which alcohol use and behavioral health issues are addressed.

Other drugs may result in significant effects on the ability to perform safety-sensitive functions, even if they are not prescription drugs, and the results of FAA aircraft accident toxicology findings suggest that over-the-counter antihistamines may have a greater impact on aviation safety than do recreational drugs or alcohol. The U.S. aircraft accident investigations of fatalities have demonstrated that unapproved drugs often contribute to, or are a causal factor for, an accident. In a study of recent accident victims, alcohol was present in 5.6%, controlled substances (including opiates, cocaine, methamphetamine, and marijuana) in 8.6%, and over-the-counter medications in 14.9% of 1,683 fatalities (56).

TOXICOLOGY CONCLUSIONS

Aerospace activities present unique problems to the practice of toxicology. Reactive, toxic compounds are integral parts of aviation and space exploration; therefore, opportunities for exposure are commonplace. These are most often through inhalation; however, ocular and dermal exposures can be injurious as well. Medical personnel must recognize that some compounds elicit delayed effects, and that even trace contaminants can adversely affect health if the exposures are continuous and prolonged. Exposures are invariably to a group of compounds, and certain individuals may be unusually susceptible to trace pollutants. Astronauts must be considered a susceptible population for many toxicants. Risks in space flight originate from predictable sources and also for unpredictable sources, such as combustion events.

The safety-sensitive personnel associated with commercial aviation require stringent control to ensure that drugs and alcohol do not increase the risk of accidents.

INTRODUCTION TO MICROBIOLOGY

The environment is an important element of human existence on Earth. Similarly, the closed environmental microcosm of spacecraft/space stations plays a crucial role in human survival in space. Favorable physical characteristics such as gas composition and temperature of the internal environment are essential for human habitation, whereas unacceptable biological and chemical contamination levels of the habitable space environment can make continued habitation impossible. Establishment and maintenance of a comfortable, safe, and productive environment is a top priority. Generally, we think of infectious diseases as the major microbiological-related concern, but other adverse effects as shown in Figure 9-1 may also affect the safety and performance of astronauts. In addition to infectious diseases, allergies, volatile chemicals, and microbial toxins may cause crew discomfort and reduced productivity. Plant pathogens may endanger food supplies, microbial contamination may result in food spoilage and degraded water quality, and severe accumulation may lead to performance degradation of critical spacecraft systems (e.g., life support system). In addition to being inherent contaminants of our environment, microbes release a wide array of chemical contaminants into the environment.

Microbial risks to astronauts generally do not include those associated with high-risk public health diseases such as *Mycobacterium tuberculosis* and hepatitis viruses. This is because the crewmembers are screened for such diseases before flight and no credible exposure route is available for such microorganisms during spaceflight. Crewmembers are a major source of microorganisms on spacecraft, and most of these microbes released into the space environment are generally harmless along with some opportunistic pathogens such as *Staphylococcus aureus*. Microbial contaminants may also originate from payloads and experiments, equipment, water and food, consumables, and the environment before launch. These contaminants along with those of human origin contaminate the ISS and may cause concerns related to function of critical spacecraft systems (e.g., life support system). Our approach to mitigating these risks is discussed in the subsequent text.

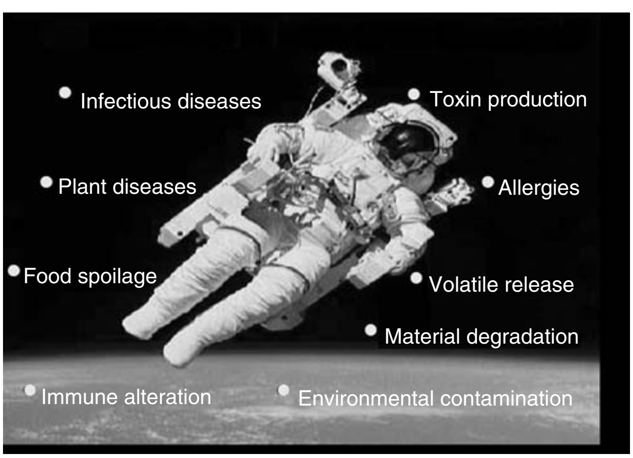


FIGURE 9-1 Adverse effects of microorganisms in space environment.

Approach to Risk Mitigation Aboard the International Space Station

Acceptability Limits To ensure optimum crew productivity aboard the ISS, acceptability limits for microbial contamination of breathing air, spacecraft surfaces, drinking water, and food have been established (Table 9-1). These standards were created for human space flight by utilizing existing industry standards (e.g., Environmental Protection Agency guidelines for drinking water) and expert panels. Preflight monitoring of resupply spacecraft, new ISS modules, water, food, equipment, and materials, and periodic monitoring of the ISS environment assesses conformance with the acceptability limits.

Air Numerous diseases are disseminated through the air. Many respiratory viruses, such as influenza, varicella-zoster virus, respiratory viruses, bacterial diseases including tuberculosis, and fungal diseases such as aspergillosis are commonly spread by airborne routes. Gravity is an effective means of limiting the spread of airborne infectious diseases as larger droplets fall rapidly to Earth. In normal gravity on Earth, aerosol particles of 40 μm and larger settle to the floor within 60 seconds (57). The longer airborne infectious agents stay in the breathing air, the greater the risk of infecting a crewmember. In the reduced gravity environment of spaceflight, generation of bioaerosols (aerosols of microbes or microbial products) is particularly problematic because aerosolized droplets are more easily generated and remain suspended in the air until they collide with a surface or are captured on an air filter.

The breathing air is monitored on a quarterly basis with a small, handheld, battery-operated air impaction sampler (Burkard) as shown in Figure 9-2. Space flight limitations and constraints require in-flight monitoring to utilize small, portable devices that are battery powered, easy to operate, low maintenance, and easily calibrated. Accuracy and reliability are additional essential factors. Eighty-five liters of air are impacted on culture medium plate for bacteria and fungi. After incubation, the bacteria and fungi can be visualized and quantified by visual count. Low levels of airborne bacteria and fungi are found onboard the ISS. The most commonly recovered bacterial genera from the air on the ISS are *Staphylococcus, Micrococcus*, and *Bacillus*. These bacteria are commonly associated with humans (except *Bacillus*, a common spore-forming environmental bacterium). *Aspergillus* and *Penicillium* are the prevalent fungal (mold and yeast) genera found (58). These are common environmental molds. Levels of bacteria and mold

TABLE 9-1

Microbiology Acceptability Limits for International Space Station

Parameter		*Preflight*	*In-flight*
Air	Total bacteria:	300 CFU/m^3	1,000 CFU/m^3
	Total fungi:	50 CFU/m^3	100 CFU/m^3
Surfaces	Total bacteria:	500 CFU/100 cm^2	10,000 CFU/100 cm^2
	Total fungi:	10 CFU/100 cm^2	100 CFU/100 cm^2
Water	Total count:	50 CFU/1 mL	
	Total coliforms:	nondetectable/100 mL	
Food	Total aerobic count:	≤20,000 CFU/g	
	Escherichia coli:	≤1 CFU/g	
	Coagulase-positive *Staphylococci:*	≤1 CFU/5g	
	Salmonella:	≤1 CFU/25g	
	Clostridium perfringens:	<100 CFU/g	
	Yeasts and molds:	<100 CFU/g	

CFU, colony-forming units.

aboard the ISS have been consistently below acceptability limits and far below levels found in typical homes, offices, and previous spacecraft. These low levels of contaminants are attributed to the inclusion of high-efficiency particulate air (HEPA) filters in the original ISS design.

Surfaces Many diseases, such as influenza and tuberculosis, can be transmitted to others through human contact or contacting inanimate objects known as *fomites* (e.g., doorknobs). Accumulation of microorganisms within the spacecraft can lead to other undesirable effects (Figure. 9-1) including degradation of performance of critical spacecraft systems such as the environmental control system. Growth media–filled slides are used quarterly for the collection of bacteria and fungi from 25 cm^2 of selected surfaces. After suitable incubation, these samples can be analyzed and quantified on-orbit (similar to air samples) providing crewmembers data on current environmental conditions. Results from the ISS indicate that bacteria of human origin (e.g., *Staphylococcus*)

FIGURE 9-2 Inflight monitoring of International Space Station breathing air.

are the most commonly recovered bacterial genera (59). *Penicillium, Aspergillus*, and *Cladosporium* are the prevalent genera of mold. Surface contamination levels on the ISS are consistently low and below acceptability limits. More than 7 years of data from the ISS verify the effectiveness of a rigorous housekeeping schedule, monitoring, and constant vigilance by the crews. However, infrequently, excessive fungal growth has occurred in most spacecraft, including the ISS (Figure 9-3). When surfaces exceed the acceptability limits for bacteria or fungi (Table 9-1), the surface is cleaned by using either a Russian supplied disinfectant wipe (hydrogen peroxide and quaternary ammonium compound) or a U.S. supplied wipe (quaternary ammonium disinfecting compound).

Water and Food More than 200 diseases are transmitted through food (60). The Centers for Disease Control and Prevention (CDC) estimate that 76 million cases of foodborne illnesses and 5,000 deaths occur in the United States yearly (61). Norwalk-like viruses, Campylobacter, and Salmonella are major causes of foodborne illnesses (61).

Food is analyzed before flight to ensure the microbiological safety according to Table 9-1. Water is tested on orbit for bacterial content as shown in Figure 9-4. A measured volume of water is passed through a filter trapping the suspended bacteria. After addition of growth media and incubation, the bacteria can be visually quantified. Typically, the bacterial load is low and within acceptability limits (Table 9-1). The high cost of transporting drinking water (potable) to the ISS requires the reclamation and recycling of humidity condensate on the ISS to reduce the volume and mass of potable water that must be resupplied from the ground. The reclaimed and processed humidity condensate is supplemented by water provided by the space shuttle and by ground-supplied water. Potable water aboard the ISS is available from three water ports, including a dispenser of

FIGURE 9-3 Fungal contamination on International Space Station.

ground or shuttle-supplied water and two ports from the humidity condensate recovery system. A detailed description of these systems (62) and analysis hardware has been described previously (63).

Postflight analysis of water samples have identified the predominant genera recovered, which included *Sphingomonas, Ralstonia, Pseudomonas*, and *Methylobacterium* species. These species are commonly found in water supplies. Although not uncommon in water, the opportunistic pathogens, *Stenotrophomonas maltophilia* and *Pseudomonas aeruginosa*, were recovered from the potable water systems a few isolated times (59,64). All three ISS potable water sources are routinely analyzed for coliform bacteria, a common indicator of fecal contamination and the potential for disease causing microorganisms (e.g., hepatitis B or gastrointestinal bacterial pathogens). It is important to note that no indication of coliforms or major waterborne pathogens has been detected in ISS potable water. The closed ISS environment and occupation by exceptionally healthy astronauts precludes most pathogens associated with waterborne diseases. Therefore, no medically significant bacterial contamination of the potable water system aboard the ISS has occurred.

FIGURE 9-4 Analyzing bacterial content of drinking water on the International Space Station.

Payloads Payloads may contaminate the environment of spacecraft. Astronauts are exposed to many biological materials, a small number of which may be hazardous. Most risks associated with biohazardous materials are microbiological.

Microbiological risks associated with biohazards are assessed specifically for each spacecraft, space station, or space habitat depending on a number of factors. These include the specific microorganism identified, the infectious dose, pathogenicity, disease associated with agent, total number of microbes used in the investigation (allowing for growth during the mission), the biosafety level, and availability of vaccine and treatment options.

Flight payloads are proposed by payload organizations from countries around the world. All payloads undergo a rigorous safety evaluation by the Payload Safety Review Panel (PSRP) at NASA's JSC in Houston. The evaluation requires the preparation and submission of a safety data package by the payload organization. One aspect of the overall safety review is biosafety. The JSC Biosafety Review Board reviews all payloads that contain biological materials. Some payloads may not inherently be classified as *biohazardous*, but they may harbor hazardous microorganisms. For instance, animals included in the payload for investigational purposes may harbor microorganisms that are hazardous. Animals must meet the requirements on microbial agents defined by the JSC Committee for the Protection of Human Subjects document. Other payloads may similarly harbor microbes requiring evaluation. For example, plants and soil (or soil stimulants) may harbor fungi and bacteria that may present a hazard to the crew and/or the spacecraft. In essentially all cases, the microbial hazards can be contained.

Risk Mitigation Countermeasures Risk reduction should begin in the design phase of spacecraft and space habitats. Experience has shown that early identification of risks followed by design and implementation of effective risk mitigation countermeasures is the most cost-effective approach. Many microbiological risks can be reduced or eliminated by this approach. For example, the risk of airborne infectious/allergenic agents and nuisance particulates can be greatly reduced by placing safeguards into the air-conditioning and distribution system. Inclusion of HEPA filters into the air circulation system has proved to be very effective in maintaining air with very low concentrations of bacteria, fungi, viruses, and particulates aboard the ISS. Various allergens including fungal spores, pollen, and dust mites are effectively removed as well. HEPA filters are 99.997% effective in removing particulates greater than 0.3 μm in diameter. HEPA filtration is the most effective and proven technology to provide breathing air with very low levels of microbial contaminants. When possible, engineering and design solutions should be sought to eliminate environmental contaminants associated with adverse health effects or contamination of essential systems (e.g., life support system). This is much more cost effective and often eliminates the problem instead of pursuing only monitoring approaches.

The selection of materials used to construct and outfit spacecraft is highly important in discouraging inappropriate microbial growth. Nonporous surfaces are more easily cleaned and disinfected than porous surfaces (e.g., fabric). Surfaces containing antimicrobial substances should be considered. Vigilance with emphasis on water leaks, spills, and condensate is very effective in early detection of conditions that eventually lead to microbial growth. Generally, routine cleaning of exposed surfaces with cleaners containing surfactants to loosen and emulsify contaminants is sufficient to meet established acceptability limits for bacteria and fungi on spacecraft internal surfaces. However, disinfectant wipes are available for use when indicated. All cleaning and disinfecting substances must be compatible for use in closed environments that recycle air and water for crew consumption.

Maintaining environmental conditions unfavorable for sustained growth of microbial contaminants is essential to prevent or control environmental microbial contaminants. Spacecraft characteristically provide a shirt-sleeve environment for crew comfort. Unfortunately, such temperatures promote microbial growth. However, controlling availability of water (e.g., humidity and surface condensate) is essential in controlling microbial growth. Prevention of water condensation on surfaces, water leaks and spills, and holding relative humidity to 60% and below are effective controls.

Approaches for Mars Missions

Lessons have been learned from the ISS and earlier programs and must be applied to spacecraft and space habitats for Mars missions. Inclusion of HEPA filters in the ISS resulted from lessons learned from the space shuttle and the Russian Mir experiences. Microbiological risks can be identified and levels of acceptable risks must be defined. These risks can be mitigated by early development and implementation of effective countermeasures beginning with the spacecraft design phase. Monitoring must be independent of the Earth and limited. Experience on a lunar habitat may demonstrate that no routine monitoring is necessary. Instead, preventive routine cleaning of critical surfaces or systems and crew vigilance of environmental conditions (e.g., odors, leaks) with the capability to remediate (e.g., disinfect) heavily contaminated areas may be the approach.

Careful preflight and in-flight vigilance of crew health should limit infectious agents to opportunistic pathogens that are manageable in astronauts with normal immunity. Clinically significant decreases in immunity (65,66) and/or increased virulence of microorganisms (67) could present medical challenges.

MICROBIOLOGY CONCLUSIONS

Microbiological agents can adversely affect the health, safety, and performance of astronauts. In addition to direct effects on crewmembers, microorganisms can degrade the environment and the performance of critical spacecraft systems, ultimately jeopardizing mission objectives. More than 7 years of in-flight and postflight environmental data clearly demonstrate that the ISS environment is microbiologically safe and consistent with a clean, healthy human habitat.

A Mars mission can be undertaken successfully, but lessons learned from previous space flight programs, and especially the lessons to be learned from years of human occupation of lunar habitats must be applied to the mission. Intervention early in the design phase of Mars vehicles and surface habitats can provide microbial countermeasures such as HEPA filters for air, use of antimicrobial materials in areas prone to microbial growth such as internal components of the environmental control and life saving systems (ECLSS) (e.g., water coolant loops), advanced disinfection techniques for drinking water, and others. Prevention must still be the hallmark, and many risks can be mitigated before flight. A healthy and fit crew is essential, and sustaining healthy immunity is essential. All environmental microbiological planning (acceptability limits, etc.) assume a normal immune response. Medically significant diminishment of the immune response will increase the risk considerably.

REFERENCES

1. Major RH. *A history of medicine*. Springfield: Charles C Thomas Publisher, 1954:3–65, 383–394, 640–713.
2. Witschi H. Profiles in toxicology, Fritz Haber: 1868–1934. *Toxicol Sci* 2000;55:1–2.
3. Bowen E. *Knights of the air. The epic of flight*. New York: Time-Life Series, 1980:36–42.
4. Bauer LH. Airplane dope poisoning. Chapter 16. *Aviation medicine*. Baltimore: Williams & Wilkins, 1926:171–173.
5. Parmet AJ. Toxicology in aviation. *Aeromed Train Dig* 1990;4(1): 43–52.
6. Osbon HG. *Apollo toxic hazard board-definition and procedures*. Memorandum from the Chief Engineer, Apollo Space & Information Systems Division, dated 21 October 1963.
7. National Academy of Sciences. *Atmospheric contaminants in spacecraft, report of the panel on air standards for manned spaceflight*. Washington, DC: National Academy Press, 1968.

8. National Research Council. *Atmospheric contaminants in spacecraft, report of the panel on air quality in manned spacecraft of the Committee on Toxicology*. Washington, DC: National Academy Press, 1972.
9. National Aeronautics and Space Administration. *Apollo 1: the fire*. 1967 http://history.nasa.gov/SP-4029/Apollo_01a_Summary.htm, accessed 2/22/07, 2007.
10. Nicogossian AE, LaPinta CK, Burchard EC, et al. Chapter 3. Crew health. *The Apollo-Soyuz test project medical report*. NASA SP-411. 1977:11–24.
11. James, JT. *Toxicological assessment of the noxious odors produced by the Orbiter refrigerator/freezer during the STS-40 mission*, Memorandum SD4/91–308, 1991.
12. James JT, Beck S, Martin M, et al. *Toxicological assessment of the ISS atmosphere with emphasis on the metox canister regeneration*. Paper 2003-01-2647 at the International Conference on Environmental Systems, July 7–10, Vancouver, Canada, 2003.
13. Klaassen CD. Principles of toxicology. In: Klassen C, Amdur M, Doull J, eds. *Toxicology: the basic science of poisons*, 3rd ed. New York: Macmillan, 1986:11–32.
14. Witschi HR, Last JA. Toxic responses of the respiratory system. In: Klaassen C, ed. *Toxicology: the basic science of poisons*, 6th ed. New York: Macmillan, 2001:515–534.
15. Jenkins AJ, Cone EJ. Pharmacokinetics: drug absorbtion, distribution and elimination. In: Karch SB, ed. *Pathology of drug abuse*, 3rd ed. Boca Raton: CRC Press, 2001:151–202.
16. Eaton DL, Gallagher EP. Mechanisms of aflatoxin carcinogenesis. *Annu Rev Pharmacol Toxicol* 1994;34:135–172.
17. Rozman KK, Klaassen CD. Absorbtion, distribution and excretion of toxicants. *Toxicology: the basic science of poisons*, 6th ed. New York: Macmillan, 2001:91–112.
18. Kondroshov V, Rothenberg SJ, Chettle D, et al. Evaluation of potentially significant increase of lead in the blood during long-term bed rest and space flight. *Physiol Meas* 2005;26:1–12.
19. Teeguarden JG, Deisinger PJ, Poet TS, et al. Derivation of a human equivalent concentration for n-butanol using a physiologically based pharmacokinetic model for n-butyl acetate and metabolites n-butanol and n-butyric acid. *Toxicol Sci* 2005;85:429–446.
20. James JT, Gardner DE. Exposure limits for airborne contaminants in spacecraft atmospheres. *Appl Occup Environ Hyg* 1996;11:1424–1432.
21. Holden PR, Tugwood JD. Peroxisome proliferator-activated receptor alpha: role in rodent liver cancer and species differences. *J Mol Endocrinol* 1999;22:1–8.
22. National Research Council. *Methods for developing spacecraft water exposure guidelines*. Washington, DC: National Academy Press, 2000.
23. Wong KL. Carbon dioxide. *Spacecraft maximum allowable concentrations for selected airborne contaminants*. Vol. 2. Washington, DC: National Academy Press, 1996:105–187.
24. Sood A, Bee JB, Beckett WS. Chapter 57-Occupational lung diseases. In: Stein JH, ed. *Internal medicine*, 5th ed. St. Louis:Mosby, 1998: 471–476.
25. Wong KL. Carbon monoxide. *Spacecraft maximum allowable concentrations for selected airborne contaminants*. Vol. 1. Washington, DC: National Academy Press, 1994:61–90.
26. US Environmental Protection Agency. *Potential implications of genomics for regulatory and risk assessment applications at EPA*. Report EPA 100/B-04/002. 2004.
27. Thomasson HR, Crabb DW, Edenberg HJ, et al. Alcohol and aldehyde dehydrogenase polymorphisms and alcoholism. *Behav Genet* 1993;23:131–136.
28. Agency for Toxic Substances Disease Registry. *Jet fuels JP-5 and JP-8. CAS 8008-20-6*. 1999.
29. Chao YE, Gibson RL, French LAN. Dermal exposure to jet fuel (JP-8) in US Air Force personnel. *Ann Occup Hyg* 2005;49(7): 639–645.
30. McCollum DK. Maintaining Skydrol hydraulic fluid. *Aircraft Maint Tech* 2006:2783.
31. Harbison RD. Alcohols and glycols. In: Harbison RD, ed. *Hamilton and Hardy's industrial toxicology*, 5th ed. St. Louis: Mosby, 1998:217–234.
32. *NASA/Kennedy space center fact sheet*. Accessed at: http://www-pao.ksc.nasa.gov/nasafact/count2.htm, 8-3-07, 2007.
33. MacNaughton MG, Stauffer TB, Stone DA. Environmental chemistry and management of hydrazine. *Aviat Space Environ Med* 1981;52(3):149–153.
34. Martin GA, Cardinale MA, Tafer JR. In: Harbison RD, ed. *Space operations. Hamilton and Hardy's industrial toxicology*, 5th ed. St. Louis: Mosby, 1998:589–596.
35. Freudenrich C. *How space shuttles work*. Found at: http://www-pao.ksc.nasa.gov/nasafact/count2.htm. Accessed 8-3-07, 2007.
36. Dejournette R. Rocket propellant inhalation in the Apollo-Soyuz astronauts. *Radiology* 1977;125:21–24.
37. Potter AE. *Environmental effects of shuttle launch and landing. Ch19*. STS-1 Medical Report, NASA Technical Memorandum 58240. December 1981.
38. Nicogossian AE, Parker JF Jr. Space medicine and physiology, Chapter 19. *Toxic hazards in space operations*. NASA SP-447, 1982:285–292.
39. Wong KL. Ammonia. *Spacecraft maximum allowable concentrations for selected airborne contaminants*. Vol. 1. Washington, DC: National Academy Press, 1994:39–59.
40. Wong KL. Ethylene glycol. *Spacecraft maximum allowable concentrations for selected airborne contaminants*. Vol. 3. Washington, DC: National Academy Press, 1996:232–270.
41. Weiland PO. *Living together in space: the design and operation of the life support systems on the International space station*. Vol. I. NASA/TM-1998-206956, 1998.
42. Weiland PO. *Living together in space: the design and operation of the life support systems on the International space station*. Vol. II. NASA/TM-1998-206956, 1998.
43. Lam C-W. Bromotrifluoromethane. *Spacecraft maximum allowable concentrations for selected airborne contaminants*. Vol. 3. Washington, DC: National Academy Press, 1996:21–52.
44. Wong KL. Methanol. *Spacecraft maximum allowable concentrations for selected airborne contaminants*. Vol. 1. Washington, DC: National Academy Press, 1994:149–167.
45. McCoy JT. Formaldehyde. *Spacecraft maximum allowable concentrations for selected contaminants*. Vol. 5. Washington, DC: National Academy Press, 2008. (approved for publication)
46. Tomaszewski C. Carbon monoxide. In: Ford MD, ed. *Clinical toxicology*. Philadelphia: WB Saunders, 2001:657–668.
47. ASHRAE. *Commercial Aircraft Cabin Air Quality Research Report*, June 29, 2006.
48. MacLeon S. Carbon dioxide. In: Harbison RD, ed. *Hamilton and Hardy's industrial toxicology*, 5th ed. St. Louis: Mosby, 1998:162–164.
49. Gaier JR. *The effects of lunar dust on EVA systems during apollo missions*. NASA/TM-2005-213610, Cleveland: Glenn Research Center, 2005.
50. Taylor LA, James JT. *Potential toxicity of lunar dust, space resource utilization roundtable VIII*. At http://www.isruinfo.com/index.php?page=srr$_8$. Accessed 8-3-07, 2007.
51. Aircraft accident report in-flight breakup over the Atlantic Ocean Trans World Airlines Flight 800 Boeing 743-131, N93119 near East Moriches, New York July 17, 1996. NTSB Report Number: AAR-00-03, 8/23/2000. http://www.ntsb.gov/Publictn/2000/AAR0003.htm
52. Martin GA, Cardinale MA, Tafer JR. Space operations. In: Harbison RD, ed. *Hamilton and Hardy's industrial toxicology*, 5th ed. St. Louis: Mosby, 1998:589–596.
53. NASA Kennedy Space Center Chronology, 1981, Part 1, 84–85 and Part 2, 181–195.
54. NASA Astronaut health care system review committee. *Report to the administrator*. February-June, 2007.

55. http://www.nasa.gov/audience/formedia/features/astronautreport.html. Accessed 17-02-08.
56. Chaturvedi AK, Smith DR, Soper JW, et al. Toxicological findings from 1587 fatal civil aviation accidents between 1998–2003. *Aviat Space Environ Med* 2005;76:1145–1150.
57. Pierson DL, McGinnis, MR, Viktorov AN. Microbiological contamination (chapter 4). In: Sulzman FM, Genin AM, eds. *Space biology and medicine, volume II: life support and habitability*. Washington, DC: American Institute of Aeronautics and Astronautics, 1994:77–93.
58. Pierson DL. American Society for Gravitational and Space Biology. Microbial contamination of spacecraft. *Montreal Bull* 2000;14(2):1–5.
59. Castro VA, Thrasher AN, Healy M, et al. Microbial diversity aboard spacecraft: evaluation of the International Space Station. *Microbial Ecol* 2004;47:119–126.
60. Bryan FL. Diseases transmitted by food. *A classification and summary*, 2nd ed. Atlanta: U.S. Department of Heath and Human Services, 1982.
61. Mead PS, Slutsker L, Dietz V, et al. Burden of food-borne illness in the U.S. *Emerging infectious diseases*. Vol. 5, Centers For Disease Control and Prevention. 1999:607–625.
62. Koenig DW, Bell-Robinson DM, Johnson SM, et al. Microbial analysis of water in space. *Presented at the 25th International Conference on Environmental Systems*. San Diego, 1995.
63. Samsonov NM, Bobe LS, Gavrilov LI, et al. Water recovery and oxygen generation by electrolysis aboard the International Space Station. *Presented at the 32nd International Conference on Environmental Systems*. San Antonio, 2002.
64. Ott CM, Bruce RJ, Pierson DL. Microbial characterization of free floating condensate aboard the Mir space station. *Microb Ecol* 2004;47:133–136.
65. Sonnenfeld G, Taylor GR, Kinney KS. Acute and chronic effects of space flight on immune functions. In: Ader R, Felten DL, Cohen N, eds. *Psychoneuroimmunology*, 3rd ed. Vol. 2. San Diego: Academic Press, 2001:279–289.
66. Pierson DL, Mehta SK, Stowe RP. Effects of space flight-associated stress and environmental factors on reactivation of latent herpes viruses. *Psychoneuroimmunology*, 4th ed. Vol. 2. San Diego: Academic Press, 2006:851–868.
67. Nickerson CA, Ott CM, Mister SJ, et al. Microgravity as a novel environmental signal affecting *Salmonella enterica* serovar typhimurium virulence. *Infect Immun* 2000;68(6):3147–3152.

RECOMMENDED READINGS

Bruce RJ, Ott CM, Skuratov VM, et al. *Microbial surveillance of potable water sources of the International space station*. SAE Technical Paper 2005-01-2886. 2005.

James, JT. *Airborne dust in space vehicles and habitats*, Paper 2006-01-2152 in SAE Transactions of Aerospace, 380–386.

Mudgett PD, Packham NJ, Jan DL. An environmental sensor technology selection process for exploration. *International Conference on Environmental Systems*, Paper No. 2005–01–2872, SAE, Warrendale, 2005.

CHAPTER 10

Space Environments

James Perry Locke

> The two problems we face in the space program are gravity and paperwork. We can lick gravity, but sometimes the paperwork is overwhelming.
>
> —*Wernher von Braun (1912–1977)*

During the last four decades, humans have ventured beyond Earth's biosphere. Many short-duration missions to low Earth orbit (LEO) have been conducted. Humans have walked on the surface of the Moon. In space stations circling the Earth, humans have been able to live and work for months at a time. Unoccupied spacecraft have also landed on distant planets, such as Mars. This next decade will see the completion of the international space station (ISS), which will be used to gain further expertise in long-term survival in space. Knowledge gained from ISS operations will facilitate the development of the more sophisticated spacecraft life support systems needed for even bolder human spaceflight missions. The coming decades could see human missions to Mars or a return to the Moon to establish human research facilities. In the distant future, life support technology may even facilitate the creation of permanent extraterrestrial bases or colonies.

In general, the conditions found on Earth are quite conducive to human survival. With a few exceptions, humans inhabit nearly every region of the planet's landmasses. Humans modify their surrounding environment to provide more habitable conditions, but by and large, relatively little environmental modification is necessary on Earth. For the most part, humans take the intrinsic habitability of Earth's surface for granted. However, in space, the environmental conditions found are not compatible with human survival. Defining the differences in environmental conditions between those found on Earth and in space shows why this is so.

It may appear that a suitably habitable environment can be created simply by attempting to reproduce terrestrial environmental conditions within the cabin. In actuality, it is first necessary to define the detailed environmental characteristics that humans require and then match these requirements with the other design constraints. Implementing these environmental characteristics within a spacecraft can be quite challenging. Balancing these various requirements and constraints can test the limits of available technology.

Using the life support systems of actual spacecraft as examples can illustrate the concepts and challenges associated with designing the systems used to support human survival in space. Finally, discussing cutting-edge life support technology points to how these design challenges might eventually be surmounted, enabling future human missions to Mars and beyond.

THE SPACE ENVIRONMENT

The space environment is markedly different from that found on the Earth's surface and is not habitable, primarily because it lacks an appropriate gaseous atmosphere. However, there are other environmental characteristics that define the space environment that can also significantly affect human survival.

Lack of Atmosphere

Earth's atmosphere consists of a combination of temperature, pressure, and gas composition necessary for human survival on the planet's surface. The vast majority of the gas molecules that comprise the atmosphere are within 10,000 m of the surface. As distance from the surface increases, the number of atmospheric gas molecules per unit volume decreases and the number of collisions between individual gas particles decreases, causing atmospheric pressure to fall. Figure 10-1

FIGURE 10-1 Tangential view of Earth's atmosphere.

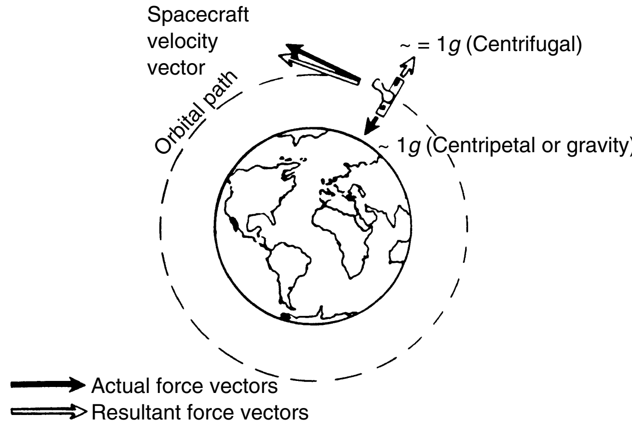


FIGURE 10-2 Representation of the balance of forces that produces weightlessness (OG) in Earth's orbit. OG, oxygen generator.

illustrates the thinning of the atmosphere away from the Earth's surface.

There are other key physiologic and engineering constraints that occur at specific altitudes within the atmosphere. Pressurized oxygen delivery masks are ineffective above altitudes of 13,000 m (43,000 ft), making cabin atmospheric pressurization necessary (see Chapter 3). Above 18,900 m (63,000 ft), the total atmospheric pressure equals the vapor pressure of water at body temperature. It is above this altitude, known as *Armstrong's line*, that the bodily fluids of an unprotected individual would spontaneously boil in a process known as *ebullism*. Above 27,000 m (90,000 ft), the atmosphere becomes too thin to support current air-breathing jet engines requiring the use of rocket motors. At altitudes above approximately 90 km (47 mi), the atmosphere is too thin to allow the use of aerodynamic control surfaces, necessitating the use of reaction motors to control the orientation of a vehicle. This is known as the *Von Karmann line*. Above altitudes of 180 to 200 km, air resistance becomes negligible, marking the true engineering boundary between the atmosphere and space. The upper limit of the atmosphere is defined as the point at which collisions between molecules become immeasurably infrequent (∼700 km). Above this is the hard vacuum of true space, known as the *exosphere*, where the number of air molecules thins to a density of approximately 1 to 20 mol/cm^3.

Altered Gravity Environments

The force of gravity is a fact of life on Earth. Humans traveling to space from Earth, traveling in space, and returning to Earth can expect to experience significant alterations in gravitational effects. At the Earth's surface, the mass of the planet exerts gravitational force equal to 9.81 m/s^2 (32 ft/s^2). This gravitational field extends for millions of kilometers beyond the surface (the Moon is trapped within this gravitational field). However, placing a spacecraft in orbit can counterbalance this gravity field, allowing the vehicle to remain in space (Figure 10-2). The speed of the vehicle must be sufficient to generate centrifugal force equal in magnitude to the planet's gravitational force at that altitude. When this is done, the vehicle will not fall back toward the surface. In other words, an orbiting object is continuously falling around the planet, although its tangential velocity prevents it from falling closer to the surface. This balancing of centrifugal and gravitational force vectors simulates the lack of true gravity, and is more properly referred to as *free fall* or *microgravity*.

The magnitude of the planet's gravitational field determines how fast an object must travel to achieve orbit. Spacecraft in LEO at altitudes of 250 to 600 km (150–350 mi) must maintain tangential velocities of 28,000 to 42,000 kph (17,000–25,000 mph). Conceivably, objects could orbit at lower altitudes, but aerodynamic friction from the Earth's atmosphere precludes this. Smaller planets exert less gravitational force, so the velocity required to reach orbit is less. Orbital velocities around Mars (where the surface gravity is one third as strong as Earth's) and the Moon (where the surface gravity is one fifth of Earth's) are much lower at comparable altitudes.

Microgravity significantly affects the habitability of space because humans are naturally adapted to the gravity of the terrestrial environment. Before the first human spaceflights proved them wrong, some scientists were worried that humans could not live without gravity (1). Microgravity does affect human health, from the immediate effects of motion sickness and possible alterations to gastrointestinal functioning to the long-term effects of bone demineralization. Further discussion of the medical risks of microgravity is addressed in Chapter 28.

As noted earlier, traveling to space using current rocket technology requires reaching orbital velocities. To return from space, spacecraft must lose velocity by using the Earth's atmosphere as a brake. These large changes in velocity impose significant acceleration and deceleration forces on spacecraft and their inhabitants. Mercury astronauts experienced acceleration forces of up to 8 G_x (chest to back) for short periods of time (2). In contrast, shuttle passengers now experience a maximum of 3 G_x during launch. During reentry, Soyuz passengers can experience up to 10 G_x. Shuttle passengers experience lower forces (1.3 G_y), but for longer duration, and in a different orientation (head to foot).

Changing a spacecraft's linear or rotational velocity while in space also subjects passengers to acceleration forces.

Gravitational forces can also be simulated by centrifugal force caused by rotating a spacecraft about its axis. In the future, rotating spacecraft might have the pseudogravity of centrifugal force to mitigate the adverse effects of weightlessness.

Orbital Mechanics

Although a detailed discussion of orbital mechanics is beyond the scope of this text, an explanation of basic orbital nomenclature illustrates the impact of orbital mechanics on spacecraft operations. Orbital mechanics play an important role in the capability of launching payloads into orbit. As shall be seen, orbital mechanics also play a central role in determining the radiation exposure a spacecraft receives.

While launching a rocket into Earth orbit, the angle of the launch vector with regard to the equator defines how much acceleration is needed to reach the orbit and hence how much payload can be lifted into it. This is because the Earth's rotation profoundly influences what orbits are achievable. The tangential velocity of the Earth's surface is greatest at the equator (1,040 mph or 1,734 km/hr), and drops off to zero at the Earth's poles. When launching a rocket in an eastward direction, the rotational velocity of the Earth can be applied to the amount of velocity needed to reach orbit. The lower the latitude, or more southerly the launch site is, the greater the available rotational velocity is and the less rocket propellant will be required. Attaining orbit is most efficient at the equator and most difficult at the poles. Changing the angle of the launch vector changes the angle of inclination of the resultant orbit. Orbits are typically referred to by this angle of inclination. Launching a vehicle due eastward from the equator would give an orbital inclination of 0 degrees. From any given launch site, the most efficient possible orbital inclination is equal to the latitude of the launch site. Therefore, a rocket launched due eastward from Kennedy Space Center in Florida will enter a 28-degree orbit, and a vehicle launched eastward from the Baikonur launch site in Kazakhstan will have an orbital inclination of 51.6 degrees. Any rocket launched from the Earth's pole will have a 90-degree inclination. Orbits of different inclination can be achieved from a given launch site by shifting the launch vector northward or southward from due east, but this comes at the expense of significant increases in the amount of propellant required to reach orbit. Therefore, a space shuttle launched from Kennedy Space Center to the ISS (which is in a 51.6-degree orbit) can carry much less payload than if it were launched into a 28-degree orbit. Launching a rocket westward requires extrapropellant to counteract the Earth's rotation, making such orbits prohibitively inefficient.

Radiation

The space environment is relatively devoid of matter, but it can be full of energy, especially in the vicinity of a sun such as ours. This energy comes in the form of electromagnetic radiation and high-energy particles. The electromagnetic radiation found in space is of many wavelengths, from low-frequency microwave radiation and below to infrared (heat), visible light, and ultraviolet wavelengths and all the way to high-frequency x-ray radiation and γ radiation and beyond. Particles such as protons, electrons, neutrons, α particles, and heavy ions may be of inconsequential mass but can be highly energetic. The Earth's atmosphere and surrounding geomagnetic field partially shield the planet's surface from space radiation. During spaceflight outside of LEO, spacecraft can leave this protective envelope, increasing the risk of exposure of the passengers to potentially harmful radiation.

Ionizing versus Nonionizing Radiation

Particle and electromagnetic radiation can be grouped and classified as either ionizing or nonionizing radiation. Ionizing radiation has sufficient energy to knock material from atomic structures during a collision, which can release further electromagnetic or particle radiation. Astronauts have reported that, when their eyes are closed, they occasionally see small flashes of light, evidence that the energetic products of nuclear collisions occurring within the eye can activate retinal visual receptor cells (3). If ionizing radiation particles collide with atomic nuclei inside human cells, the resultant energy release can damage cellular DNA. This genetic damage can lead to cell death or the cellular mutation that underlies carcinogenesis.

Nonionizing electromagnetic radiation may not be energetic enough to directly damage genetic material, but it can still be quite harmful. Solar ultraviolet electromagnetic radiation, unattenuated by the atmosphere, can cause severe sunburn and retinal burns after only seconds of exposure. Solar infrared radiations that can cause significant thermal loading, are discussed later.

Ionizing radiation comes from several sources: galactic cosmic radiation (GCR), solar radiation, and geomagnetically trapped radiation. Because the altitude and trajectory of a spacecraft's flight affect the amount of radiation received from these sources, this information is used to calculate projected radiation dose profiles that are used during mission planning.

Galactic Cosmic Radiation

GCR is radiation that originates outside of the solar system and is probably generated by the cataclysmic extrasolar events such as supernovae. GCR is predominantly particle radiation, consisting of α particles, β particles, and the heavier nuclei such as tin or lithium. These particles often travel at tremendous velocities, imparting them with very high energy usually in the range of 0.3 to 2 GeV (10^9 eV). Although there is a relatively constant flux of GCR into the solar system, the amount of GCR in the region of planetary bodies is influenced by solar activity. Because planetary magnetic field strength increases during periods of high solar activity, scattering of charged GCR charged particles away from the planetary environment is maximal during these periods, thereby decreasing the amount of GCR that penetrates the geomagnetic belts.

Although they can be diverted by electromagnetic fields, the high velocities of galactic charged particles allow them to penetrate through meters of solid matter, making passive shielding (e.g., the aluminum walls of the spacecraft) essentially useless. Fortunately, its high velocity and low flux density makes it likely that GCR will pass through an astronaut without striking any atomic nuclei, yielding minimal energy transfer to the cellular components. Increased amounts of passive shielding increases the likelihood that GCR particles will collide with nuclei within the shield. These nuclear collisions may release a shower of secondary electromagnetic radiation and high-energy particles (usually neutrons) that may have more adverse biologic effects than the original particles (4).

Solar Wind and Solar Cosmic Radiation

The solar wind consists of proton–electron plasma that is ejected from sun at velocities of 400 to 500 km/s (240–300 mi/s). This solar wind or solar cosmic radiation (SCR) is the most variable portion of the background space radiation and changes density considerably during the Sun's 11-year cycle of activity. During periods of high solar activity, SCR can be the major source of the astronaut's space radiation exposure, especially when the solar particles become trapped in the Earth's geomagnetic belts. In periods of minimal solar activity, the trapped radiation belts are not as energized, and GCR becomes the predominant source of exposure. Solar flares can cause a 1,000-fold increase in the radiation flux of the SCR in the form of solar particle events (SPEs).

Solar Flares and Solar Particle Event Radiation

Magnetic disturbances on the Sun's surface can lead to solar flares, which consist of electromagnetic radiation, as well as SPEs that consist of high-energy protons. The SPEs can contain particles of sufficient energy and flux density to result in a lethal radiation exposure to an unshielded space traveler unfortunate enough to be caught within it (5). Fortunately, the particle radiation released during such events is not uniformly distributed in all directions, so not every SPE will expose a spacecraft in a given location to the maximum flux of radiation emitted. The rate of onset and rate of dissipation of an SPE radiation flux density can also be quite variable and can vary in duration from minutes to days. SPEs typically occur during the active period of the solar cycle.

Unfortunately, it is very difficult to predict exactly when an SPE might occur, as well as the duration and flux of the radiation that the SPE will produce and how significant a spacecraft's exposure to that radiation will be. Radiation detectors orbiting the Earth can measure the increases in solar electromagnetic radiation that accompany solar flares, and other devices can detect increases in proton flux density. Detection of significant increases in electromagnetic and particle radiation indicate that an SPE may be occurring. Spacecraft may then be alerted, so that crewmembers can conceivably take shelter in a shielded "safe haven" until the radiation flux returns to acceptably low levels (6).

The Earth's magnetic field is an effective shield against even the most massive SPEs. The radiation contained by the largest SPE ever recorded (August 1972) would have been undetectably low to a space shuttle traveling in a typical orbit under the Earth's magnetosphere; however, it could have posed a health hazard to an inadequately shielded spacecraft traveling in a higher orbit.

Magnetically Trapped Radiation

The size and nature of the Earth's geomagnetosphere was examined by Dr. James Van Allen and his team in the 1950s. Generated by the rotation of the Earth's molten ferromagnetic core, the Van Allen belts are toroidal structures that encircle the planet in an extremely powerful magnetic field. The thickness of these geomagnetic belts depends on the latitude, the thickest portion being near the equator. Note that the Earth's magnetic pole is slightly offset from its rotational pole. Instead of striking the Earth's surface, the high-energy particles of GCR and the solar wind become trapped within these magnetic belts, oscillating along the lines of magnetic force. The amount of trapped particles in these belts increases during periods of high solar activity.

The Van Allen belts are compromised of two layers, an inner belt (extending from altitudes of 300–1,200 km) that contains trapped protons and heavy ions and an electron-containing outer belt (extending from altitudes of ~10,000 km to altitudes of more than 55,000 km, depending on the solar wind). Because of their toroidal shape, the magnetic fields of the Van Allen belts can lie close to the outer surface of the atmosphere at extreme northern or southern latitudes. (These low-lying regions are known as the *auroral horns*.) This is illustrated in Figure 10-3. At extreme latitudes, impact of trapped high-energy particles with the atmosphere can ionize the atmospheric gas molecules, causing the spectacular light shows of the Arctic Aurora Borealis and Antarctic Aurora Australis.

Most orbital flights occur at altitudes below the majority of the volume of these magnetic belts, providing some protection to spacecraft occupants from space radiation. However, because the rotational axis of the Earth does not coincide with its magnetic pole, this discrepancy causes the magnetic belts to dip to altitudes as low as 160 to 320 km (95–215 mi) in the region known as the *South Atlantic anomaly* (SAA). Orbiting spacecraft passing through this region are exposed to particle radiation trapped within the magnetic field that is equal in intensity to radiation found at altitudes of 1,300 km (750 mi). Most radiation received during shuttle missions with typical low-inclination orbits (28 degrees) occurs as a result of passing through this zone. The percentage of orbits that pass through the SAA depends on the angle of inclination. The higher inclination (51.6 degrees) orbit of ISS pass through the center of the anomaly less frequently than 28-degree low-inclination orbits. However, because the size of the anomaly increases at higher altitudes, a spacecraft orbiting at high altitude (e.g., ISS) will be exposed to more radiation than a spacecraft traveling along the same orbital track at a lower altitude.

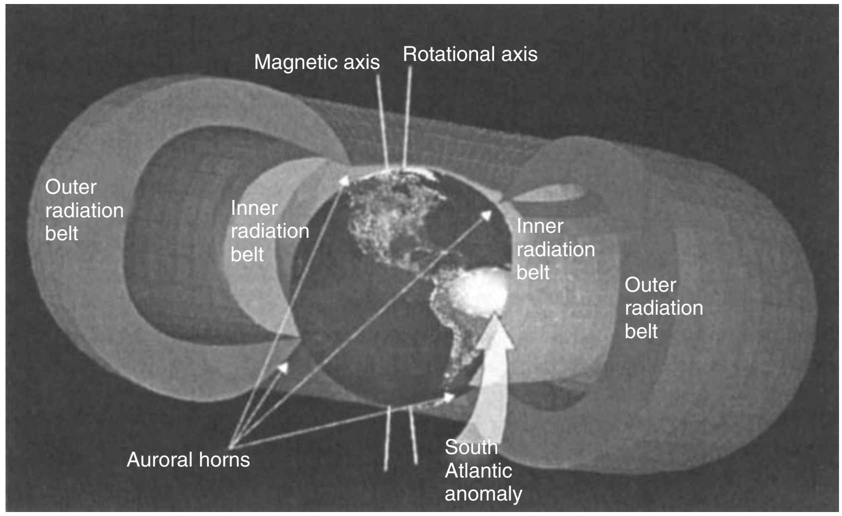


FIGURE 10-3 Van Allen radiation belts.

Also, high-inclination orbits pass through the auroral horns, where the geomagnetic belts dip closer to the surface, thereby increasing exposure to trapped belt radiation. Because the geomagnetosphere does not cover the Earth in polar regions, spacecraft traveling in very high-inclination orbits are also exposed to a higher dose of GCR.

Radiation on the Moon and Mars

Because it lacks both an atmosphere and a geomagnetic field, the Moon's surface is not shielded from radiation as Earth's surface is. The lunar surface, composed of rock and powdered debris from meteor impacts (*regolith*), is therefore subjected to steady bombardment by GCR and solar radiation, including the occasional SPE. Mars also lacks a significant geomagnetic field, but its thin atmosphere of carbon dioxide does provide some radiation shielding. Because a planet's spherical mass shields a given point on its surface from a geometrical proportion of cosmic radiation (this is known as 2π *shielding*), the radiation experienced on the surface of these bodies is roughly half of what would be experienced in similar regions of free space. Planetary materials can also be used as radiation shielding. If an inhabited lunar station were established, covering it with a thick coating of *regolith* could serve as an effective radiation shield for everything except high-energy protons and neutrons (7). However, if the *regolith* coating were insufficiently thick, secondary radiation scattering from nuclear collisions within the layer could paradoxically worsen the radiation exposure to the crewmembers beneath it.

Thermal Instability

The Earth's atmosphere not only provides pressurization and oxygenation but also serves as an insulating blanket, maintaining remarkably stable temperatures on the surface. The terrestrial atmosphere regulates the temperature changes caused by the day/night cycle. This temperature-regulating ability is strongest at sea level, where the mass density of the atmosphere is greatest, and degrades with increasing altitude. Anyone who frequents Alpine climates is familiar with the intense solar radiation during the day, followed by rapid temperature drops after sunset as the daylight's heat radiates away.

In space, there is no atmosphere present to regulate temperature. Radiation is the sole method of energy transfer. At the Earth's distance from the Sun, solar energy radiation is sufficient to heat the exposed surfaces of objects to temperatures that can cause significant thermal damage to materials and equipment. The intensity of solar radiation decreases with increasing distance from the Sun. In the farther reaches of the solar system, the Sun provides little heat. Also, because there is no atmosphere in space to retain heat, heat dissipates very rapidly. Even at the Earth's distance from the Sun, surfaces not exposed to sunlight typically have temperatures far below the freezing point of water. Marked temperature differences between the sun-exposed and nonexposed surfaces of any given object can impose significant thermal stress.

Humans cannot tolerate these thermal stresses. Astronauts working outside of their spacecraft in spacesuits during extravehicular activities (EVAs) can simultaneously experience intolerably hot and intolerably cold temperatures. They must be protected from these massive fluctuations in temperature to survive. The environmental control systems necessary to maintain thermal stability is discussed later.

Space Debris

Earth's gravitational field attracts solid objects, most of which enter the atmosphere and burn up as shooting stars. These objects are called *meteorites* or *micrometeorites*, depending on their size. It is estimated that as much of 10,000 metric tons of micrometeorite material reaches the Earth's surface daily. However, it is estimated that only approximately 200 kg of this material is suspended in orbit within 2,000 km of the surface at any given time. Of this micrometeoroid material, the vast majority is extremely small (much less than 0.1 mm in diameter). Although small, their extreme velocities give these particles tremendous kinetic energy. A millimeter-sized object moving at orbital velocities would easily penetrate the thin aluminum skin of a standard spacecraft.

Of greater concern is the large amount of orbital debris created by human activity. It is thought that there are millions of kilograms of human-related space debris suspended within LEO. This human-created orbital debris is not only primarily composed of very small objects such as paint flakes and aluminum oxide particles from solid rocket fuel but also consists of fragments of launch vehicles, old satellites, and even tools dropped by astronauts. The North American Air Defense Command (NORAD) tracks orbital debris larger than 10 to 20 cm in diameter, of which there are approximately 6,000 in orbit. Objects smaller than this are not routinely tracked.

Examination of the surfaces of spacecraft exposed to the orbital environment for extended durations indicate that collisions with orbital space debris occur frequently, but these collisions usually involve extremely small particles. The construction of typical spacecraft is sufficient to protect them from collisions with micrometeoroids of this small size. The spacesuits of astronauts performing EVAs offer some protection from such impacts. To further decrease the risk of micrometeoroid impacts, mission planners orient the shuttle so that the bulk of the vehicle protects the spacewalking astronauts from most potential micrometeoroid impacts.

Isolation

Although essentially unrelated to habitability, physical isolation is a characteristic of the space environment that significantly affects human survival. Physical resources of one form or another are always on hand on the Earth's surface. The sophistication of modern transportation technology ensures that a journey between any two points on the Earth's surface requires only a matter of hours. Supplies, replacement equipment, and additional personnel are seldom very far away. In contrast, orbiting spacecraft are separated from their terrestrial points of origin by both distance and velocity.

Because spacecraft in space are so completely separated from the resources of the terrestrial surface, the spacecraft must carry everything that the astronauts need to complete their mission or until they are resupplied. Apart from solar energy, space contains no resources that can feasibly be collected to replace used materials.

Rendering physical assistance to a spacecraft in need would require tremendous expenditures of resources, if such assistance were even possible. Even for a spacecraft to abort its mission and return to the protective confines of Earth can be a monumental task, as attested to by the experiences of Apollo XIII crew, who successfully struggled to guide their damaged spacecraft back from the Moon.

This physical isolation also affects communication. Large swaths of orbital tracks remain out of range of current radio communication equipment, cutting spacecraft off from contact with ground mission control for minutes at a time. Component failure in space–ground communications systems could leave orbiting astronauts to face dangers without the assistance of experts on the ground.

REQUIREMENTS FOR HUMAN SURVIVAL IN SPACE

The differences between the space and terrestrial environments discussed previously show why humans cannot survive in space without the provision of a suitably habitable environment, either within a spacecraft, space station, or spacesuit. There are many factors that must be considered when creating the appropriate environmental conditions. First and foremost are the human habitability requirements. In the spacecraft environment, how these habitability requirements are achieved depends on other external factors relating to the mission objectives and the constraints of available technology.

Human Habitability Considerations

Although *habitability* could be defined as being conducive to survival, an exact definition of the concept is elusive. Like the concept of health, environmental habitability is easier to define by its absence than by its presence. Humans live in an environment that is innately habitable to them, which gives them an implicit understanding of the environmental conditions that they can tolerate. Moreover, when given a choice, they demonstrate a high degree of specificity in selecting environmental conditions that they prefer. Yet when asked to define the characteristics that define an optimally habitable environment, most people would focus on nonessential elements, taking for granted the conditions that they truly need to survive. Because it is difficult to define, habitability is perhaps best considered in terms of how environmental conditions affect humans.

The primary habitability consideration for a given environment is that humans must be able to survive. This implies that the most basic physiologic parameters are met. The longer the human must survive, the more environmental components must be supplied.

Survival is not the only consideration that defines a habitable environment. The environmental conditions must also be of sufficient quality to permit the occupants to perform their required tasks. A wildly tumbling space capsule may keep its inhabitants alive, but the tumbling may keep them from reaching a critical control panel. Environmental conditions may also cause human performance to degrade with time. How quickly this degradation occurs depends on how poor the environmental conditions are.

The final consideration that defines environmental habitability relates to the health and safety of its inhabitants. Humans may be able to survive in a given environment and may be able to perform their required duties there, but their health could be affected by being there. Exposure to radiation may produce no obvious symptoms or decrements to performance, yet can cause significant health problems in the future.

Maintenance of a Breathable Atmosphere

The key to atmospheric habitability is to maintain the oxygen concentration at a partial pressure of oxygen (P_{O_2})

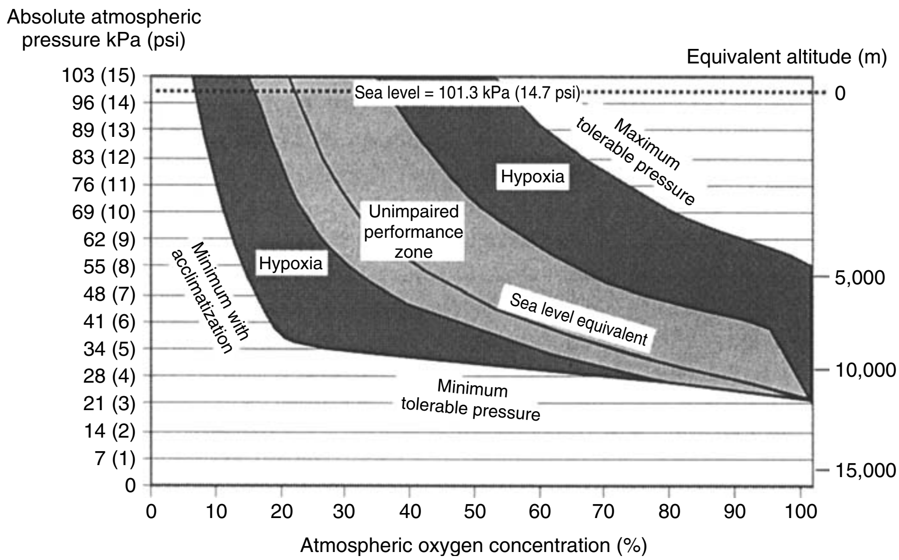


FIGURE 10-4 Human physiologic limits of atmospheric pressure and oxygen concentration.

near the sea-level partial pressure of 21 kPa (3.1 psi or 160 mm Hg) to avoid adverse physiologic effects such as decreased night vision, impaired memory and cognitive performance, unconsciousness, and death. These effects can begin within a few seconds of oxygen deprivation, depending on the degree of hypoxia, so it is extremely vital that the oxygen supply be uninterrupted (2). On the other hand, higher P_{O_2} starting at 32 kPa (4.7 psi or 240 mm Hg) can also lead to physiologic problems, such as lung irritation and damage and central nervous system impairment. Figure 10-4 illustrates the ranges of atmospheric pressure and oxygen concentration that are acceptable for use in spacecraft. For safety reasons, oxygen concentration and partial pressure must also be kept as low as possible to minimize the risk of fire. Current guidelines require that American spacecraft atmospheres nominally contain less than 23.5% oxygen at sea-level atmospheric pressure. Russian spacecraft may exceed these concentrations.

The terrestrial atmospheric level of carbon dioxide (CO_2) is 0.032 kPa (0.0046 psi or 0.24 mm Hg). Higher concentrations of carbon dioxide can have adverse physiologic effects, including hearing loss, headache, decreased cognitive performance, and eventually unconsciousness and death. To avoid these adverse effects, atmospheric CO_2 partial pressures should be maintained below 1.0 kPa (0.15 psi or 7.6 mm Hg) (2). However, levels up to 1.6 kPa (0.20 psi or 15 mm Hg) can be tolerated for short periods during emergencies. Because CO_2 is continually generated during normal metabolic respiration, it must be constantly "scrubbed"' from the atmosphere of a spacecraft habitat so that acceptably low concentrations are maintained.

Trace atmospheric contaminants also pose a significant potential problem for spacecraft atmospheres and can cause both short- and long-term health problems. There are many potential sources of atmospheric contamination. Metabolic by-products (such as methane and hydrogen sulfide) and spilled cleaning and experimental chemicals are potential sources of contamination, as are toxic propellants (such as hydrazine) or coolants (ammonia) that leak into the cabin or are brought in from the outside on the surfaces of spacesuits. Some organic polymer materials can slowly release toxic volatile organic compounds (such as toluene), and the thermal breakdown of other materials release other chemicals. Fires can release toxic products of combustion. It is essential to monitor the spacecraft environment for these trace contaminants and to have an effective method for removing them. For each of these atmospheric contaminants, spacecraft maximum allowable concentrations (SMACs) can be defined to ensure that atmospheric concentrations of a given contaminant are within safe levels (8). SMACs for many potential contaminants can be based on terrestrial regulatory standards for individual compounds, defined by such organizations such as the American Council of Governmental Industrial Hygienists (ACGIH), the Occupational Safety and Health Administration (OSHA), and the Environmental Protection Agency (EPA). When terrestrial exposure guidelines for a given compound do not exist (e.g., hydrazine), available research data is used to determine appropriate SMACs. SMACs have been defined for approximately 200 potential atmospheric contaminants.

Temperature Regulation

Although humans can survive in a relatively wide range of temperature and humidity conditions, the range that is comfortable for working and living is fairly narrow and depends on the level of activity. Ideal temperatures range from 18°C to 27°C (65°F–80°F) and ideal humidities range from dew points of 4°C to 16°C (40°F–60°F) [relative humidities (RH) from 25%–70%]. Optimal human performance requires staying within this comfort zone of temperature and humidity to provide a shirtsleeve working environment. Humans also prefer some degree of control of their environmental temperature and humidity to match their comfort with their level of activity (2).

Potable Water Supply

For humans to survive, they require a steady supply of potable water for drinking, cooking, and personal hygiene. Potable water can be procured from stored supplies, recycled from wastewater, recovered from atmospheric condensation, or generated from hydrogen/oxygen fuel cells. Potable water supplies must contain acceptably low concentrations of organic, inorganic, and microbial contaminants. Water quality must also be monitored to ensure that quality standards are maintained throughout the duration of the mission. Spacecraft water exposure guidelines (SWEGs) have been established for potential contaminants of potable water to ensure that water of sufficient purity is available (9).

Minimize Radiation Exposure

As mentioned previously, the space environment confers radiation exposure significantly greater than is found in typical terrestrial environments. This radiation exposure may cause a variety of adverse physical effects, leading to short- and long-term medical consequences. The impact of radiation on human health in the aerospace environment is discussed in greater detail in Chapter 11. By minimizing exposure to radiation, the risk of associated adverse sequelae can be minimized; however, because this radiation exposure in the space environment cannot be eliminated, the principle of maintaining exposure levels as low as reasonably achievable (ALARA) is used. Vehicle shielding and careful planning of mission profiles can decrease spacecraft crewmembers' exposure to radiation. However, these methods cannot prevent crewmembers' exposure to significant levels of radiation during spaceflight.

Ensuring that crewmembers' career radiation exposure (both short-term and lifetime cumulative) remains within acceptably safe levels minimizes the associated risks. This requires that crewmembers' radiation exposure during spaceflight be carefully measured. Acceptable radiation exposure limits are then used to ensure that crewmembers are placed at unacceptable risk by their radiation exposure history. If crewmembers' cumulative or interval radiation exposures approach these limits, their spaceflight activities can be limited to ensure that accepted exposure guidelines are not exceeded. Astronauts' career radiation exposure limits are based on the exposure limits set for terrestrial radiation workers by the National Council of Radiation Protection (NCRP), which allows a maximum annual radiation exposure of 0.05 Sv (5 rem). However, because of the unique work environment encountered during spaceflight, NCRP recommendations drafted in 1989 set radiation exposure standards for astronauts in LEO that were considerably higher than allowed for terrestrial workers [e.g., they permit annual radiation exposures of the blood forming organs of up to 0.5 Sv (50 rem)] (10). At present, the NCRP is revising the radiation limits recommended for LEO, taking into account new data and new concepts of acceptability of risk. The new space radiation exposure standards will probably accept a 1% increase in lifetime fatal cancer risk attributed to the radiation exposure. They will account for astronauts' gender and age at time of exposure and will allow less radiation exposure than the prior standards (11). Different standards may be required for future missions beyond LEO.

Nutritional Support

Adequate daily food intake is necessary to replace metabolic energy stores and to provide the biologic substrate for repairing and maintaining bodily tissues. Micronutrients, vitamins, and minerals must also be supplied to maintain health. Humans prefer that food be palatable, with attention given to ensure acceptable food temperature, appearance, texture, taste, and aroma. Food supplies that meet these metabolic, nutritional, and palatability requirements must be available for the duration of the spacecraft's mission, which requires adequate food preservation, storage, and preparation capabilities (12).

Waste Management

Wastes generated in space habitats consist of several general types: solid wastes (such as used food containers), moist solid wastes including feces and vomitus, liquid wastes including urine and wastewater, and gaseous wastes. Other waste subcategories include biologic and sharp hazard wastes. Such wastes must be removed or isolated from the habitable cabin to limit unhygienic and potentially hazardous environmental contamination.

Human Factors Requirements

Humans must maintain adequate health and fitness, both physically and psychologically, if they are to maintain their ability to perform tasks. If they are unable to do this, their performance ability degrades with time. Their surrounding environment plays an integral role in their ability to maintain adequate psychologic and physical health. Human factors and human performance are discussed further in Chapter 24.

Adequate sleep is crucial for human performance. To maintain long-term human performance, an environment must be provided that is conducive to sleep or that at least does not actively interfere with sleep. Appropriate light/dark cycles facilitate proper *circadian* cycling. Noise, vibration, and other disturbances should be minimized to promote proper sleep, as well as to prevent their adverse affects on human health and task performance.

Habitat design itself can also significantly affect human performance. Illumination sufficient for the performance of tasks must be provided. The volume, spatial arrangement, and decor of the spacecraft habitat should ideally be designed to provide a comfortable environment. Windows may be included to provide connection with the outside environment.

On the other hand, isolation from the terrestrial environment imposes other psychologic stressors. Opportunities to communicate with family and friends on Earth help crewmembers to maintain a crucial link to their terrestrial lives. News of current events should be provided so crewmembers do not feel out of touch with their homes. To avoid boredom during long missions, entertainment must be provided.

Mission Requirements

The goals and objectives of the spacecraft's mission strongly influence what type of life support systems are necessary to supply the required environmental parameters, as well as the type and amount of supplies that are needed. Crew size determines the amount of air, food, and water that will be needed per day during the mission, as well as how much CO_2 and other metabolic waste products will need to be processed. The more the crewmembers, the more habitable volume the spacecraft must provide. Space station designers may also have to account for occasional increases in the number of inhabitants during crew transfer and supply missions. To a given extent there is an economy of scale, so a relatively modest increase in life support system capacity may result in the ability to have significantly more crewmembers.

Mission duration also determines the amount of supplies that will be necessary. For short-duration missions, all necessary supplies can be taken along. However, as mission duration increases, the weight of supplies quickly becomes prohibitive. Expendable supplies must be replaced with regenerable supplies. Waste products may also be used *in lieu of* fresh supplies (e.g., using the water by-product from fuel cells as the source of potable water instead of bringing a separate water source). The longer the mission, the more carefully supplies and resources must be conserved.

The scope of reclamation and recovery of usable resources from waste streams of spacecraft life support systems is known as *mass loop closure*. Consumable resources, such as oxygen, potable water, and food are converted by metabolic activity into waste by-products, and their mass is potentially lost to reuse. Figure 10-5 shows the daily usage of consumable resources that would be expected during a space mission, as well as the amount of waste by-product that would be produced. Recycling and recovering usable resources from waste by-products in effect returns material to the stores of consumable resources, which decrease the total amount of supplies required by a mission. This process of recovery of usable mass from waste by-products is therefore known as *mass loop closure*. Systems that do not recycle any useful material for reuse have no mass loop closure and are referred to as *open* systems. In general, all short-duration spacecraft have open systems because resources are not regenerated from waste by-products. It must be noted that scrubbing metabolically derived CO_2 from the cabin atmosphere does not constitute mass loop closure because the oxygen in the CO_2 is not regenerated and reused. Total mass loop closure, in which all waste mass is recycled into usable material so that no extra supplies are needed, is possible in theory, but not in practice. The water recovery systems used in recent space stations represent the first practical efforts of mass

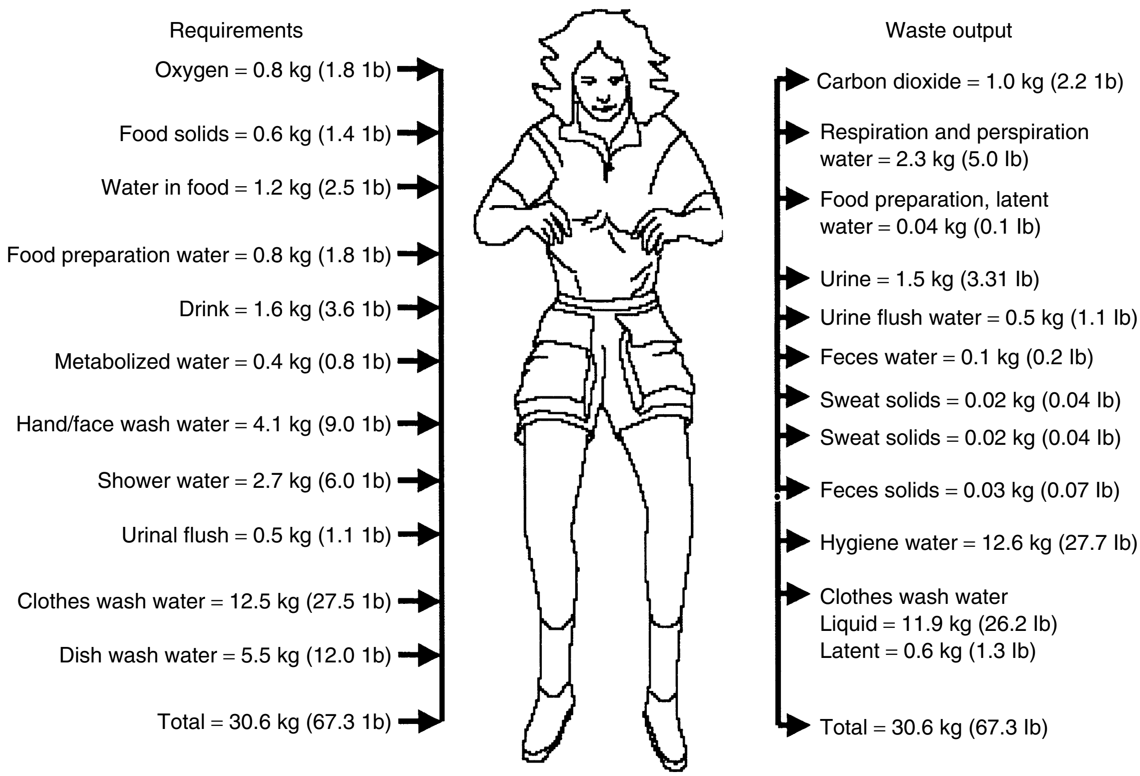


FIGURE 10-5 Mass balance of human consumable requirements and waste output. (Adapted from Wieland P. *Designing for human presence in space: an introduction to environmental control and life support systems.* (NASA RP-1324). Huntsville: NASA Marshall Spaceflight Center, 1994, with permission.)

TABLE 10-1

Mass Loop Closure—Levels and Mechanisms

Levels of Mass Loop Closure	*Description of Closure*	*Mission Scenarios*	*Mission Duration*
Totally closed	Closed except for losses due to leaks, EVAs, etc. (e.g., biologic life support)	Lunar settlement, Mars settlement	Permanent
Solid waste recycling	Recovery of solid waste (e.g., for use as fertilizer for plants)	Lunar base, Mars base	Decades
Food production	Fresh food grown to supplement stored food	Future space stations, Mars mission	Decades, years (no resupply)
O_2 recycling	Oxygen from carbon dioxide recovered for reuse	Future long-duration missions	Years
Water recycling	Water recovered from atmospheric condensate, wastewater for reuse	ISS, Mir	Years
—	—	Skylab, Mir	Months
Totally open, using regenerable techniques	Reduced expendables (e.g., use of molecular sieve instead of LiOH for CO_2 removal)	Extended duration Orbiter, Rover habitat	Weeks
Totally open, using nonregenerable techniques	All mass brought along or resupplied with no reuse (waste vented or stored)	Mercury, Gemini, Apollo, Space Shuttle	Days

EVA, extravehicular activity; ISS, international space station; LiOH, lithium hydroxide.

loop closure. However, for long-duration missions, such as to Mars, much greater mass loop closure will be necessary. Table 10-1 shows various levels of mass loop closure and the mechanisms used to achieve those levels, along with practical examples.

The destination of the spacecraft not only determines the consumable resources required for the specified mission duration but also affects the design of the life support system, especially in terms of reliability and maintainability. For spacecraft that remain in LEO, faulty or damaged equipment may be replaced with relative ease. However, if a device fails during a mission to Mars replacing it may be impossible, so it must be extremely reliable. In such situations in which replacement is impossible, devices should be designed so that they can be repaired using available skills, equipment, and materials. Such robustness and resilience are essential design qualities of equipment used for exploration-class missions.

Technical Requirements

When designing spacecraft life support systems, the human and mission requirements can be used to generate the technical requirements, such as how large the cabin must be, how much oxygen and water must be supplied, and so on. Because spacecraft life support systems are composed of a number of complex subsystems, careful consideration must be given to how the various components are integrated.

First, life support subsystem components must efficiently perform their required tasks with minimum of wasted consumables. To ensure that this is done, the various life support system components must be strongly integrated with one another (Figure 10-6). As shall be seen, it is often difficult to separate the functioning of the thermal control system from the humidity control system, on which the atmospheric moisture recovery system is dependent. The capabilities and shortcomings of one subsystem strongly influence the functions of the other components. Life support systems may also be affected by other equipment and devices within the spacecraft. For example, thermal control systems must account for the heat generated by avionics equipment.

When spacecraft dock with each other, their life support systems must interact. Differences in the underlying operational parameters of the life support systems of the involved vehicles must be accounted for if such dockings are to be successful. As shall be seen, Russian and American life support systems have very different operating principles and philosophies. Integrating these systems in the two segments of the ISS has been quite challenging.

Life support systems must also integrate with their human occupants. The systems must meet human physiologic requirements. They must also be operable and maintainable by humans. Human–systems integration also incorporates the concepts of reliability and safety.

Technical Constraints

Several technical constraints limit what solutions are available to meet the requirements for spacecraft life support systems that were outlined briefly. First and foremost of these are the restrictions imposed by the spacecraft design itself. There are finite limits to the size and mass of objects that can be placed in orbit by current rocket technology. Such launch vehicle payload limitations restrict the size and weight of the spacecraft habitable volumes and configurations and

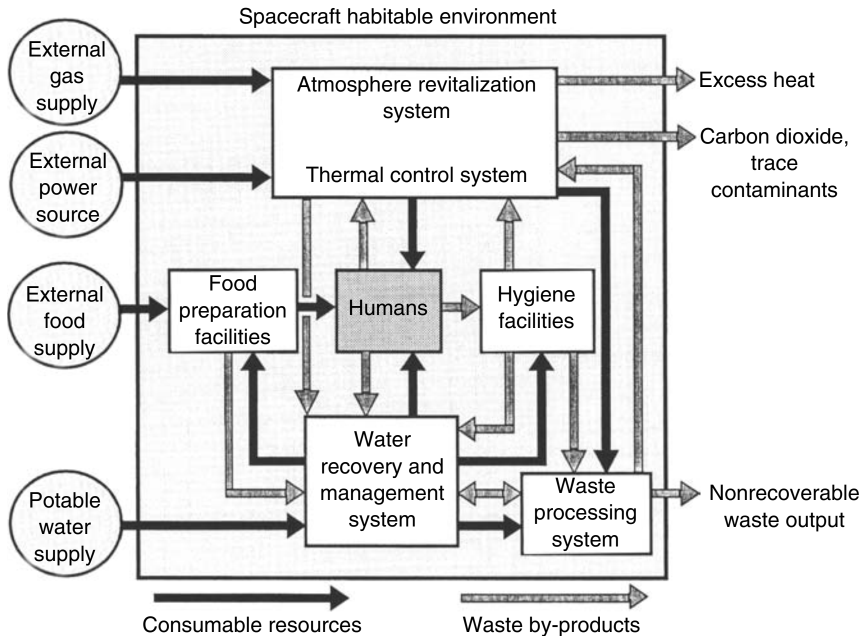


FIGURE 10-6 Schematic of the subsystem integration of a spacecraft habitable environment.

significantly affect the amount of resources with which the spacecraft can be supplied. Because of payload limitations, increasing the mission supply requirements without being able to increase the amount of available supplies necessitates a greater degree of mass loop closure.

Limitations to technology also limit the capabilities of spacecraft life support systems. As discussed later, it may not be technically feasible or possible to reach the degree of mass loop closure required for long-duration space missions, at least with the available payload volume. Very tight mass loop closure may be possible using currently available biologic technology, but such systems would be extremely large—too large to send into space. Nonbiologic physical-chemical methods may also be used for resource recovery and mass loop closure, but working systems have yet to be developed. Significant advances must be made in these areas of life support design before advanced resource recovery systems become feasible. It may also be possible to recover usable materials (e.g., water, oxygen) from planetary bodies, if these resources are present and available in adequate quantities.

The space environment itself imposes strict constraints on life support system design. Designing life support equipment that function in microgravity is challenging because solids, liquids, and even gases do not behave the same as in the terrestrial environment. For example, because separating liquids from gases is not easy without gravity, it is difficult to design an effective shower for use in space, and water storage tanks become complex devices. The vacuum of space also affects materials. Outgassing, or the loss of volatile components to the vacuum of space, can change the physical and chemical properties of a material. Solid materials can sublimate away at a faster rate in the vacuum of space than in the terrestrial environment (in an analogous process, sharp knives sitting unused for long periods become dull as molecules sublimate from the sharp edges of the knife). This process can lead to significant erosion of materials in space. Because there is no gas layer between them in space, closely adjacent materials may diffuse into one another a kind of cold welding process. These properties must be considered when selecting materials to be used in the vacuum of space (13).

Given these formidable requirements and constraints, designers of spacecraft life support systems have had to overcome many challenges. Examination of the evolution of the components that make up the spacecraft life support systems provides practical examples of the concepts involved in their design.

SPACECRAFT ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS

What environmental control and life support systems are chosen for a given spacecraft habitable environment depends on matching the human habitability requirements with the technical, mission, reliability, and safety constraints imposed by mission requirements. As was discussed previously, the nature of these various subsystems and components is often strongly influenced by how they are integrated. Historic examples illustrate the principles involved in the design of these subsystems, which gives an appreciation for the organization and functioning of the various subsystems and components. These subsystems and components can be organized by function, with some prioritization with regard to the criticality of the individual functions.

Atmospheric Control and Supply System

The life support cabins of the American Mercury, Gemini, and Apollo spacecraft contained 100% oxygen atmospheres at 34.5 kPa (5.0 psi or 260 mm Hg), yielding a PO_2 slightly higher than that of standard air (the PO_2 of terrestrial sea-level air is 21.4 kPa (3.1 psi or 160 mm Hg). A low pressure, oxygen atmosphere was chosen because (a) it offered the lowest total atmospheric pressure, allowing for the lightest possible pressure vessel; (b) a single gas atmosphere minimized complexity of the atmospheric control system; and (c) lack of nitrogen eliminated the risk of decompression sickness (DCS) during EVAs (14). The slightly hyperoxic atmospheric composition was well tolerated during short-duration missions. A pure oxygen atmosphere was also used during ground testing, in which the cabins were overpressurized to 110.2 kPa (16.0 psi or 830 mm Hg) to avoid structural damage. Such hyperbaric oxygen conditions dramatically increase the risk of fire. This was tragically demonstrated during the Apollo I fire in January 1967, which took the lives of three astronauts during hyperbaric cabin testing on the launch pad (15). Because adequate atmospheric nitrogen concentrations decrease atmospheric flammability and lower the risk of fire, an atmosphere of 40% nitrogen and 60% oxygen was used during all subsequent ground operations. After launch, cabin pressure bled down to the operational level (34.5 kPa, 5.0 psi, or 260 mm Hg), while the oxygen content was enriched to 100% (16). Astronauts prebreathed pure oxygen in their spacesuits for 3 hours before launch to avoid DCS resulting from depressurization. (DCS is discussed later.) During reentry and descent to the Earth's surface, the cabin was repressurized to avoid structural damage.

Because of the risk of fire in pure oxygen atmospheres and of the potential for adverse physiologic effects resulting from long-term exposure to hyperbaric oxygen, a 72% oxygen and 28% nitrogen atmosphere at 34.5 kPa (5.0 psi or 260 mm Hg) was used in Skylab, yielding an oxygen partial pressure slightly higher than found in sea-level air. EVAs could be performed without requiring the prebreathing of 100% O_2. Between missions, Skylab was depressurized to 13.8 kPa (2.0 psi or 102 mm Hg) and allowed to decay down to 3.45 kPa (0.5 psi or 26 mm Hg) until the arrival of the next crew (17).

The space shuttle was the first American spacecraft to have an Earth-like atmospheric mixture—22% oxygen and 78% nitrogen at a total pressure of 101 kPa (14.7 psi or 760 mm Hg). An Earth-like atmosphere is advantageous because (a) its content of inert nitrogen gas minimizes the risk of fire, (b) it is of optimum atmospheric gas density for efficient functioning of the human respiratory mechanism, (c) its gas density is adequate for atmospheric cooling of people and electronic equipment, (d) it allows equipment to be ground tested in their operating environment without expensive pressure chambers and, (e) it allows research data collected in space to be easily compared with terrestrial data. Disadvantages of an Earth-like atmosphere include (a) increased weight and complexity of atmosphere control systems and (b) increased risk of DCS with depressurization for EVAs. The cabin is typically depressurized to 70.3 kPa (10.2 psi or 530 mm Hg) the night before scheduled EVAs to decrease tissue nitrogen saturation, thereby decreasing the required duration of 100% oxygen prebreathe. To maintain acceptable cabin oxygen partial pressures, oxygen concentration is concomitantly increased to at least 23% (18). Although nominally maintained between 23.5% and 26%, cabin oxygen concentration is allowed to reach 29% at this lower cabin pressure before fire safety limits are reached (18). EVAs and the risk of DCS are discussed shortly.

In contrast, Russian spacecraft have always had more Earth-like atmospheric compositions. The Russian Vostok, Voshkod, and Soyuz space capsules all contained air-like atmospheric mixtures at approximately 101 kPa (14.7 psi or 760 mm Hg). The Salyut space stations contained a sea level–like atmosphere with a total pressure between 93.1 and 110 kPa (13.5–16 psi or 700–830 mm Hg), with P_{O_2} between 20.5 and 25.9 kPa (3.0–3.8 psi or 150–200 mm Hg). The Mir space station complex also contained an air-like nitrogen–oxygen mixture with a total pressure of 101 to 129 kPa (14.7–18.8 psi or 760–970 mm Hg) and P_{O_2} of 21 to 37 kPa (3.1–5.4 psi or 160–280 mm Hg), yielding an oxygen concentration of 21% to 40% (19). The variability in total atmospheric pressure in Russian spacecraft was due to the variability in the atmospheric oxygen partial pressure, although the nitrogen partial pressure remained relatively constant. The marked variability of the atmospheric P_{O_2} resulted from the mechanism used to generate the oxygen (more on this in the next section). However, these variations in atmospheric oxygen partial pressure were well tolerated by the crew.

The atmosphere of the ISS contains 78% nitrogen and 21% oxygen at 101 kPa (14.7 psi or 760 mm Hg), with minimal variability in composition and total pressure. This atmospheric composition was chosen to optimize the comparability of microgravity research data with their terrestrial analogs, as well as to provide a stable operating environment for ISS equipment.

In the future, other atmospheric compositions could be selected. Longer duration missions may necessitate the use of lower pressure atmospheres. Combinations of inert gases (such as helium, nitrogen, and argon) may be used to decrease inert gas partial pressures to minimize the risk of DCS. Future spacecraft may also contain different atmospheric compositions in different modules. For example, oxygen concentrations may be decreased and carbon dioxide concentrations increased in a module dedicated to plant growth in a biologically regenerated life support system.

Atmospheric Supply

The mechanisms used to supply and control atmospheric content and composition are strongly influenced by the degree of mass loop closure specified by mission requirements. Generally, using the least closed system allowed by mission requirements provides the simplest solution. Short-duration missions can usually carry adequate resources to allow for open system designs. As mission duration increases, the recycling and conservation of resources become more necessary to minimize wastage and to limit the amount of required resource reserves.

Oxygen was stored as a high-pressure gas in the Mercury spacecraft. In the Gemini spacecraft, oxygen was stored as a cryogenic supercritical fluid (pressurized to maintain the gas in a homogeneous liquid state at higher temperatures), which saved storage space. Oxygen in the Apollo spacecraft was stored both as a high-pressure gas and as a supercritical liquid. The pressure vessels of these early American vehicles allowed atmospheric gas leakage at a low constant rate, which in part prevented the buildup of atmospheric contaminants. The gas losses were replaced from stored supplies. The Apollo spacecraft design lost 1 kg (2.2 lb) of oxygen per day (16).

Aside from metabolic consumption and designed leak rates, atmospheric gas can also be lost through the operation of airlocks, leakage through seals and holes, and actual diffusion through solid materials. The rate of gas leakage from a spacecraft habitable environment is a function of the materials and designs used in its construction, along with the magnitude of its internal atmospheric pressure. Although minimizing the internal atmospheric pressure can limit gas loss, other factors also play a role in what atmospheric pressure is selected. In short, atmospheric content may be maintained by using stored supplies, by minimizing loss of atmospheric components, or by regenerating them from metabolic by-products.

Russian spacecraft are hermetically sealed to minimize gas loss and have negligible leak rates. In early Russian spacecraft, reserve gas supplies were minimal. Any nitrogen lost, for example, when depressurizing the attached airlock before EVA was not replaced. Oxygen metabolically consumed by the crew was replaced using nonregenerative cartridges of potassium superoxide (KO_2), which reacted with atmospheric water and carbon dioxide to form oxygen gas, potassium carbonate (K_2CO_3), and potassium hydroxide (19). This simple chemical system generated the needed oxygen while removing atmospheric carbon dioxide and excess atmospheric humidity. This system saved weight and made the atmospheric control system much simpler than its American contemporaries, but was not able to regulate atmospheric parameters as precisely. Although they have been successfully used in nearly all Russian spacecraft, the extreme reactivity of these chemicals makes them difficult to store and handle.

In the Vostok and Voshkod spacecraft, small high-pressure oxygen bottles were available to pressurize the cosmonauts' spacesuits during emergencies. However, because the Soyuz (Russian for "union") was designed for zero gas leakage, pressure suits were not worn in it. However, in 1971, the Soyuz 11 capsule accidentally depressurized before reentry, killing the three unsuited cosmonauts inside (19). Thereafter, the Soyuz was redesigned to include stores of compressed air to compensate for atmospheric leakage, and the cabin was modified to allow the wearing of pressure suits during launch and reentry.

Skylab, the first American spacecraft to have a mixed gas atmosphere, stored both nitrogen and oxygen as high-pressure gases. Although automatic atmospheric control systems were present, atmospheric composition and pressure were usually maintained by manually adding individual gases. Nitrogen and oxygen are also stored as high-pressure gases in the space shuttle, although metabolic oxygen is supplied from supercritical cryogenic liquid sources.

Oxygen was supplied to the Salyut space stations using the solid chemical cartridges found in previous Russian vehicles. High-pressure cylinders of compressed air were used for leakage makeup. Nitrogen and oxygen gases were not individually stored. Replacement air cylinders and oxygen generator cartridges were periodically supplied from Earth (19).

The Mir (Russian for "peace") space station embodied significant advances in atmospheric control systems. It was the first Russian spacecraft to individually store nitrogen as a high-pressure gas. It was also the first spacecraft in which oxygen was regenerated from metabolic by-products. Electrolysis was used to generate oxygen from water, including water recovered from urine. An experimental system also regenerated oxygen from metabolically produced carbon dioxide. Additional oxygen could be generated from perchlorate candles, the combustion of which yielded oxygen and salt. As in earlier Russian spacecraft, the oxygen generation systems in Mir did not allow precise control of atmospheric oxygen partial pressures. Once again, gas reserves were replenished with supplies launched from Earth.

Both the Russian and American segments of the ISS contain atmospheric control and supply systems, yielding a hybrid system. In the early construction phases, the Russian "Zvezda" service module supplies atmospheric control and supply for the entire ISS. American modules scheduled for later addition will assist in these functions. The American airlock module has attached high-pressure gas tanks to supply both nitrogen and oxygen. These supplies nominally maintain the ISS atmospheric nitrogen concentration, but the oxygen is only to be used for EVA and contingency operations. The Russian segment supplies most of the ISS oxygen using an electrolytic oxygen generation system located in the service module (similar to the system used on Mir). A solid fuel oxygen generator (SFOG) very similar to the perchlorate candles used in Mir is also used (discussed further in Chapter 3). Because of its hybrid nature, regulation of atmospheric pressure and composition is a dynamic process with complex interaction between the Russian and American atmospheric control and supply systems.

Atmospheric Revitalization Systems

Unlike aircraft, which draw fresh air in from the surrounding atmosphere to replace stale cabin air, the atmosphere within spacecraft cabins must be continually purged of contaminants. These contaminants include major metabolic by-products such as carbon dioxide and water, as well as trace metabolic by-products such as ammonia and methane, and a host of atmospheric contaminants from other sources. Because of their limited supplies of resources, spacecraft life-support systems must cleanse the internal environment of these contaminants while maximally conserving necessary atmospheric constituents. Monitoring of atmospheric contents is necessary to ensure that environmental quality is maintained.

Atmospheric Carbon Dioxide Removal Systems

An average person consumes approximately 0.84 kg (1.84 lb) of oxygen daily, using it to convert food into energy and generating approximately 1 kg (2.2 lb) of CO_2 in the process (20). Oxygen utilization and CO_2 production rates can vary because of an individual's size, diet, and activity level. As discussed previously, it is critical that atmospheric CO_2 concentrations in closed spacecraft environments be minimized to prevent adverse physiologic effects. Several methods are available to scrub carbon dioxide from the atmosphere. These methods are based on absorption (chemical or electrochemical reaction with a sorbent material), adsorption (physical attraction to a sorbent material), membrane separation, or biologic consumption.

Nonregenerative chemical absorption is the simplest method for atmospheric CO_2 removal. Lithium hydroxide (LiOH) has been used in all American spacecraft (with the exception of Skylab, which used a molecular sieve). LiOH has also been used as a supplemental CO_2 removal agent in the Russian Soyuz and Salyut spacecraft. As mentioned previously, the Vostok and Voshkod had the KO_2/KOH system to absorb CO_2. When atmospheric gas is passed through canisters containing LiOH, an irreversible chemical reaction with atmospheric CO_2 occurs, producing lithium carbonate (Li_2CO_3), water, and heat. Because this reaction is irreversible, LiOH is consumed in the process. For missions lasting more than a few days, a significant supply of LiOH is required, making regenerative CO_2 removal systems more advantageous. For example, the mass of supplies required by the space shuttle's standard CO_2-scrubbing system would have been prohibitively heavy for the 14- to 18-day missions of the extended duration mission Orbiter program (EDOMP), so the LiOH canisters were replaced with regenerable molecular sieves.

Skylab contained a regenerable CO_2 removal system that used a molecular sieve, which consisted of a two-layer zeolite bed. As the station's atmosphere was passed through it, the first layer bound atmospheric water so that the dry second layer could adsorb CO_2. Exposing the sieves to vacuum purged them of water and CO_2 and regenerated them. Thousands of kilograms would have been required if an LiOH system had been used instead. Skylab's molecular sieve system maintained atmospheric concentrations of CO_2 at an acceptably low level (0.7 kPa, 0.1 psi, or 5 mm Hg) (17). The Mir space station's four-bed molecular sieve system maintained similar CO_2 concentrations.

The ISS CO_2 removal systems are analogous to those in Skylab and Mir, using regenerable multibed molecular sieves. Humid station air first passes through a desiccant molecular sieve to remove the moisture, generating heat. The hot dry air then passes through a CO_2-scrubbing bed. The scrubbed air then passes through an already saturated desiccant bed, desorbing the moisture back into the gas to maintain atmospheric humidity. (Excess atmospheric humidity is removed elsewhere.) Saturated scrubber beds are exposed to vacuum and heated to desorb the contained CO_2. The multibed construction allows some beds to desorb carbon dioxide to vacuum while the others continue to scrub the ISS atmosphere, so the system operates continuously. LiOH containers are available should the molecular sieve CO_2 scrubber systems fail. The schematic of the carbon dioxide removal assembly (CDRA) located in the laboratory module of the American ISS segment can be seen in Figure 10-7.

During long missions, such as a mission to Mars, providing sufficient oxygen supplies for the entire mission may require that oxygen be recovered from metabolically generated carbon dioxide. Several electrochemical processes can be used to recover O_2 from CO_2 through chemical

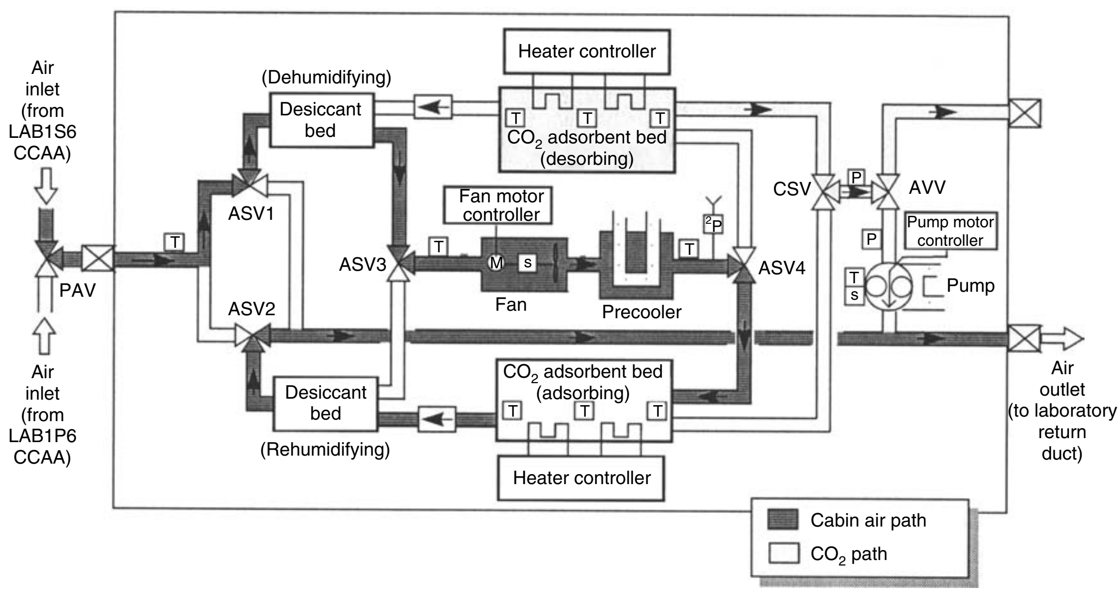


FIGURE 10-7 Schematic for carbon dioxide removal assembly located in laboratory module of International Space Station. PAV, process air valve; ASV, air selector valve; CSV, carbon dioxide selector valve; AVV, air vent valve.

reduction. CO_2 electrolysis was successfully tested on the Mir station. Further work is necessary before electrochemical carbon reduction technologies can be effectively used in spacecraft CO_2 recovery systems. On Earth, plants recover CO_2 from the air, reducing it to generate atmospheric O_2, along with carbon-based biomass. Conceivably, a biologically based environmental control system could use plants to reclaim O_2 from atmospheric carbon dioxide, while at the same time returning the carbon to the food supply as edible plant material. Work in this area is ongoing (21).

Atmospheric Trace Contaminant Removal Systems

It is essential that atmospheric concentrations of trace contaminants be maintained within acceptably safe levels. The first step to control trace contaminants is to minimize their generation and to control the types of contaminants produced. During the design phase, selecting materials to minimize offgassing and locating chemical storage and processing equipment in which contaminant generation will be minimal can reduce the amount of atmospheric contaminants to be removed. For contaminants that are present in only trace quantities, the minute gas leakage rate of a spacecraft cabin may be sufficient to maintain acceptably low atmospheric concentrations.

Microgravity also precludes the settling of atmospheric particulate matter, so cabin ventilation systems must incorporate filtration mechanisms that remove this airborne material to maintain atmospheric quality. Aerosolized microbial and viral material can be rapidly distributed through the spacecraft cabin by the ventilation system. High-efficiency particulate atmosphere (HEPA) filters must be capable of filtering the smallest infectious particles. In the American segment of the ISS, HEPA filters can trap 99.997% of bacterial material and remove any suspended particles larger than 0.3 μm in diameter (22). These filtration traps must be strategically placed throughout the ventilation system to ensure that microbial contaminants and atmospheric particulate matter are removed to maintain acceptable levels.

Substances that cannot be mechanically filtered from the atmosphere must be removed by adsorption, absorption, or catalytic oxidation into less toxic substances, such as CO_2 or water. Regenerable contaminant removal processes must be purged of contaminants to be regenerated. Nonregenerable components must be periodically replaced. In situations in which atmospheric toxin concentrations exceed the capacity of the contaminant removal systems, it may be preferable to vent the cabin atmosphere to space and replace it using uncontaminated stored gases. Skylab was partially depressurized between crews, in part to flush out atmospheric contaminants.

Water-soluble contaminants are absorbed into the water that condenses within a spacecraft's heat exchanger. The contaminated moisture condensate is then removed, freeing the heat exchanger to collect more contaminated condensate. Further processing of the collected contaminated moisture may be necessary if the reclaimed water is to be recycled instead of stored or vented overboard. (Water recovery is discussed later.)

Activated charcoal physically adsorbs high-molecular weight nonpolar organic compounds. All spacecraft to date have used activated charcoal to remove organic atmospheric contaminants. Once saturated with volatile contaminants, charcoal can be replaced or regenerated by using heat and vacuum exposure to desorb the contained organic compounds. Vacuum-regenerated charcoal beds were used in the Mir complex and are currently used in the ISS. Along with CO_2, other acidic atmospheric contaminants can be removed through physical adsorption into a regenerable molecular sieve or chemical absorption into nonregenerable LiOH canisters.

Catalytic oxidizers can be used to convert atmospheric contaminants into less toxic substances. Carbon monoxide, methane, and hydrazine (N_2H_2) can be oxidized to water and CO_2 using platinum or palladium catalysts. Ideally, these catalysts function at low temperatures with high efficiency. Prefiltration of atmospheric gas is necessary to remove organic contaminants that might precipitate on the catalyst, decreasing its efficiency. The space shuttle system uses platinum-coated charcoal packed in activated charcoal to prevent poisoning of the catalyst.

Higher temperature catalysts are more effective, but must be used carefully so that relatively innocuous chemicals (e.g., ammonia) are not overoxidized into more toxic ones (nitrogen oxides). The American segment of the ISS contains this type of high-temperature oxidative catalyst in the trace contaminant control system (TCCS). Passing the cleansed air through an LiOH cartridge removes any overoxidized compounds (Figure 10-8).

During long-duration missions, it may be necessary to recycle and conserve all trace atmospheric contaminants to maintain adequate mass loop closure. Biologic detoxification systems may be the only effective means of removing these contaminants from the environment while conserving their constituent components. Such systems could collect contaminants and transfer them to biologic detoxification systems, in which they could be stored until degraded by the contained plants, animals, and bacteria. Conceivably, such biologic systems could convert toxins into biologic substrate material that could be used in food production.

To ensure that atmospheric control systems are functioning properly, atmospheric parameters must be monitored. Real-time monitors verify that acceptable levels of major atmospheric constituents are being maintained. All spacecraft to date have had real-time atmospheric monitoring capability. The American segment of the ISS contains the major constituent analyzer (MCA), which uses a spectroscope to provide real-time measurements of the atmospheric partial pressures of oxygen, nitrogen, carbon dioxide, hydrogen, water, and methane. The Russian segment contains analogous devices.

It is also important to know if other trace contaminants are present in the cabin atmosphere. Air samples can be collected in vacuum containers and returned to Earth for

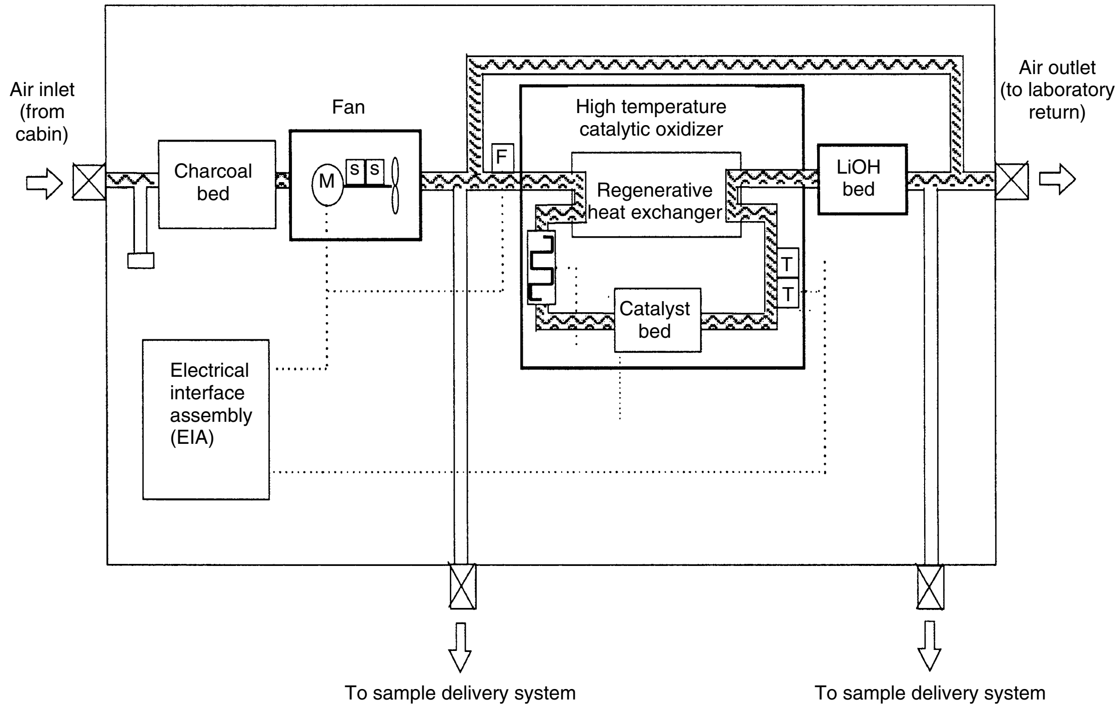


FIGURE 10-8 Schematic of trace contaminant control subassembly located in laboratory module of International Space Station. LiOH, lithium hydroxide.

subsequent analysis. Cabin air can also be passed through Draeger tubes, in which the chemical absorption of tube-specific atmospheric contaminants can cause a measurable color change. Comprehensive atmospheric contaminant analysis may be necessary for extremely long-duration missions to ensure that atmospheric quality is being maintained. If samples cannot be returned to Earth, it may be necessary to have significant atmospheric analytic capabilities onboard (23).

Thermal and Humidity Control Systems

Regulation of environmental temperature and humidity is essential, yet the characteristics of the space environment can make this a challenging task. Earth's atmosphere tends to stabilize environmental temperatures and is dense enough to use as a heat-transfer medium. In space, there is no atmosphere to serve in this manner. Solar electromagnetic radiation is sufficient at Earth's orbital distance from the Sun to cause significant heating of spacecraft. Shaded objects cool very quickly in the vacuum of space, leading to damage of cold-sensitive materials and equipment. Humans and electrical equipment can generate significant heat loads within spacecraft. Depending on size and activity level, human metabolic activity generates between 105 and 155 W (360–533 BTU/hr) per person per day. In general, spacecraft habitable environments in LEO must continually shed heat into space to maintain a comfortable shirtsleeve internal environment (20).

Spacecraft thermal control is maintained through both passive and active mechanisms. Passive mechanisms promote thermal stability using nonmoving components. In contrast, active thermal control systems mechanically transport heat from the spacecraft's interior to its surface. Once there, heat can be radiated into space or it can be rejected using evaporative cooling. The evaporative phase shift of a liquid (water) to a gas is an endothermic process. The heat of vaporization is taken from the spacecraft and dissipated into space with the evaporated liquid, which can provide significant cooling. Because there is no atmosphere on the Moon, similar radiative heat loss systems would be required. Heat could also be conducted into the lunar surface, although data indicate that such ground heat rejection systems would have to be fairly large. Likewise, because the Martian surface atmospheric gas density is so low, the construction of atmospheric convection-based heat rejection systems would be difficult. In any case, Mars' distance from the Sun and the length of the cold Martian night would yield an overall negative thermal gradient. Heat retention within a human habitat on Mars would be crucial, but heat rejection capability would not be as important.

Vehicle orientation also plays a significant role in spacecraft thermal control. Although in transit to the Moon, the Apollo spacecraft rotated at a constant slow rate to prevent localized overheating of the vehicle exterior (16). The shuttle is usually oriented with its cargo bay doors open, facing the Earth's surface, which shields the evaporator arrays in the cargo bay from solar radiation (as well as micrometeorite damage). Space stations are powered using solar energy, so they must maintain a fixed orientation to maximize solar exposure of their photovoltaic energy collectors. Because space stations maintain relatively fixed orientations relative to the Sun, their surface thermal conditions can vary significantly from location to location. Systems must be in place to stabilize spacecraft surface temperatures, warming cold regions and cooling hot regions to prevent temperature-related damage to materials and equipment.

Passive Thermal Control Systems

Passive thermal control systems use insulation, surface coatings, heat shields, and heaters to maintain thermal stability. Thermal insulation retards heat transfer and minimizes temperature gradients. Just like home insulation prevents heat from entering or escaping, spacecraft insulation performs the same function. Pure metal is a poor insulator, so spacecraft are typically coated with an insulative material or coating. Reentry vehicles must withstand extremely high temperatures and are highly insulated. The space shuttle's silicon tiles, which vary in thickness from 1 to 11 cm (0.5–4.5 in.), provide excellent thermal insulation in space, as well as during reentry. Space stations are not designed to withstand reentry, so their insulation covering is typically much thinner. Surface insulation on the ISS varies from 3.2 to 6.4 mm in thickness and is composed of multiple layers of different materials (24).

Applying the proper coating can improve temperature regulation on the surfaces of spacecraft. The thermal environment of a given surface defines what type of coating should be used. To understand which coatings should be used where, the concepts of emissivity and absorptivity must be understood. Emissivity deals with the ability of an object to emit radiant energy (heat is emitted as infrared electromagnetic radiation), and absorptivity refers to the ability of the object to absorb the radiant energy falling on it. Reflectivity is the opposite of absorptivity and should not be confused with emissivity. Emissivity and absorptivity are both typically expressed in terms of the theoretically defined ideal. Called a "blackbody," such a material would emit the theoretic maximum amount of energy from its surface. It would also absorb all radiation falling on it, giving it emissivity and absorptivity values of 1.0. In contrast, a theoretically perfect reflector would neither absorb nor emit radiant energy, so both values would be 0.0. All real materials are somewhere in between these two ideals. In real terms, spacecraft coatings experiencing high levels of solar radiation should have the lowest possible absorptivity, which can also lower emissivity. Such materials would be good at reflecting heat, but not good at emitting it. In contrast, coatings in areas designed to emit heat, such as radiator fins, should have low absorptivity and high emissivity. This concept of variable surface coatings was effectively used on Skylab, in which passive thermal control systems were the primary means of heat rejection. Similar differential surface coatings are also used on the ISS.

Some locations on spacecraft exteriors may be so thermally sensitive that coatings are not sufficient to provide adequate thermal shielding. In these instances, reflective shielding may be required to eliminate solar heating of some surfaces. Skylab was equipped with such heat shields to shade its heat radiators. When the aluminum heat shields over the radiators were damaged during launch, it became extremely difficult to maintain survivable internal temperatures, until an umbrella-like replacement heat shield could be installed during a daring space walk.

Because shaded areas of space can be extremely cold, heaters must be used to maintain external temperatures at acceptable levels. External heaters are used on the surface of the ISS to prevent moisture from condensing on the inner surfaces of the pressurized modules, to maintain equipment at proper operating temperatures, and to keep externalized equipment from being damaged by the cold. There are more than 300 heaters on the exterior of the American segment of the ISS alone (24).

Heat pipes can also be used to efficiently transport heat over short distances without moving parts. They typically contain a heat-transfer fluid. This fluid vaporizes at the heated end of the pipe and travels as a gas to the cold end, where it condenses to release the heat. The condensed liquid then returns to the hot side by capillary action, resulting in very efficient passive heat transfer from one end of the pipe to the other. Ammonia-containing heat pipes are used to maintain uniform surface temperatures in some regions of the Russian ISS modules (25).

Active Thermal Control Systems

As passive thermal control mechanisms are often insufficient to maintain adequate thermal stability inside spacecraft, active systems are usually necessary. Active thermal control systems typically are composed of heat exchangers and heat-transfer loops. Heat exchangers transfer heat from one medium to another, such as air-to-liquid, liquid-to-liquid, or liquid-to-space. Heat transport loops contain a heat-transfer medium, such as fluid or pressurized gas. Pumping the heat-transfer fluid through the heat-transfer loop mechanically transports the contained heat to the desired location. From there, a heat exchanger can be used to transfer the heat to a secondary heat-transfer loop or to reject the heat directly into space.

Although many spacecraft have passive radiators, active heat rejection systems have been used in some spacecraft. Heat exchangers can passively dissipate heat by radiating it into space or by actively dissipating heat through the evaporation of liquid into the vacuum of space. For example, water was used as the heat-transfer fluid in the Gemini, Mercury, and Apollo spacecraft. After absorbing internal cabin heat through a heat exchanger, the water was allowed to evaporate into space, taking the heat with it. Modulating the flow of water through the system regulated the cabin temperature. The shuttle also has two evaporative coolant systems (one containing ammonia and one containing water). Such evaporators can dissipate heat more quickly than passive radiators, but the associated loss of mass can become prohibitive during the extended duration missions. For this reason, passive radiators are used in most vehicles to reject heat into space.

Heat-transfer fluids vary in melting and freezing points, heat-carrying capacity, and toxicity. Which coolant to use depends heavily on the environment in which it will be used. Oftentimes, a given spacecraft may use more than one type of heat-transfer fluid, depending on the location in which it is used. Internal heat-transfer loops contain less toxic mixtures, such as water, water and alcohol, or water and glycol mixtures. Externalized heat-transfer fluids are usually more toxic, but have better physical properties (e.g., ammonia, Freon). Heat exchangers can transfer heat from one heat-transfer loop to another. For example, the space shuttle has water coolant loops internally to collect heat from the cabin. This heat is then transferred to Freon-containing heat-transfer loops that transport the heat to large radiators in the payload bay doors. These radiators are the primary means of heat rejection for the shuttle while it is in orbit. To maximize heat rejection from these radiators, the payload bay doors are kept open, and the shuttle is usually oriented to keep these radiators shaded.

In the ISS, there is minimal interaction between the thermal control systems of the Russian and American segments, with airflow through open hatches between modules being the sole means of interaction. During early construction stages, the Russian segment predominantly maintains internal thermal stability for the ISS. However, as the American segment grows, its heat rejection capacity is scheduled to become much greater than that of the Russian segment.

The Russian ISS segments contain thermal control systems similar to those used in Mir. Heat is then collected from the interior by heat exchangers, which transfer it to internal heat-transfer loops that contain an ethylene glycol and water liquid mixture. From there, the heat is transferred to an external coolant transport system that uses a silicone fluid as the heat-transfer medium. It must be noted that both the internal and external heat-transfer systems each contain two redundant loops, so that failure of any one is not catastrophic. Finally, the heat is transferred to externally mounted ammonia-containing radiators, which radiate the heat into space. The Russian active thermal system has a total heat rejection capacity of approximately 3.5 kW (24).

The active thermal control system of the American segment of the ISS is analogous to the Russian system. It is composed of an internal thermal control system (containing water) that collects and removes heat from the interior, and an external thermal control system (containing anhydrous ammonia) that rejects this interior heat into space, as well as regulates the outside surface temperatures. The internal system is comprised of two water-filled coolant loops. A low temperature (4°C or 40°F) loop provides cooling for the life support systems, and a moderate temperature loop (17°C or 63°F) collects heat from avionics and experimental equipment. These water-filled coolant loops transport heat to the external thermal control system, which is composed of two ammonia-filled loops. The external loops transfer heat to large moveable, deployable radiators that are to be mounted on the trusses outside the modules. Once complete, the American external control system will eventually have a total heat rejection capacity of 75 kW (24).

Humidity Control Systems

Human metabolic activity adds significant amounts of water to theits surrounding atmosphere. Through sensible losses (e.g., perspiration) and insensible losses (e.g., respiration), humans contribute approximately 2.3 kg (5 lb) of water vapor to the atmosphere per person per day. This atmospheric moisture must be removed from the atmosphere to maintain a comfortable environment and to minimize moisture condensation onto and adsorption into materials in the spacecraft environment, which can damage equipment and lead to microbial overgrowth.

Removing excess water vapor from the spacecraft cabin atmosphere must be done to maintain acceptable humidity levels. Atmospheric moisture can be removed in several ways. It can be physically adsorbed, chemically absorbed, or condensed onto cold surfaces. In short-term situations, nonregenerable chemical absorption or adsorption is often the simplest. Chemical desiccants can be used. For longer-duration missions, atmospheric humidity removal is best done using regenerable systems. Molecular sieves can be used as desiccant beds and are used to desiccate cabin air before passing it through CO_2-scrubbing sieves. However, these beds remove virtually all moisture from the air and do not regulate atmospheric humidity well. When using molecular sieves to remove atmospheric CO_2, the hot dry air returning from the sieves is passed back through the desiccant beds, returning the moisture to the atmosphere.

Excess atmospheric moisture is best removed using heat exchangers. Moisture condenses on the cold surfaces inside the heat exchangers, from which it is physically removed. Terrestrial dehumidifiers use this method. Gravity-dependent mechanisms then collect the condensed moisture droplets. In space, the lack of gravity makes it quite difficult to collect this condensed moisture. In the Mercury spacecraft, moisture condensate was mechanically removed from the heat exchanger with sponges and transferred to a condensation storage tank. In the Gemini and Apollo spacecraft, as well as in Russian spacecraft, wicks within the heat exchanger used capillary action to trap moisture condensate so it could be collected and removed (19). In Russian spacecraft, humidity control in the heat exchanger was also used to modulate the rate of the chemical generation of oxygen. An entirely different system is used in the shuttle and the American segment of ISS. In this system, condensate-laden air from the heat exchanger flows across a "slurper bar" that has a hydrophilic coating and contains a coolant loop, creating an air/liquid mixture. A centrifugal air–fluid separator then removes the water from this mixture, sending it to the water recovery system for purification (24).

In the Russian segment of the ISS, atmospheric moisture is condensed on the cold surface of the heat exchanger from which it is collected and passed through an air–fluid separator, collected, purified, and recycled (discussed later). The American segment of the ISS collects atmospheric moisture using a condensing heat exchanger and centrifugal separator system similar to the shuttle design. In the early stages of ISS construction, atmospheric condensate recovered

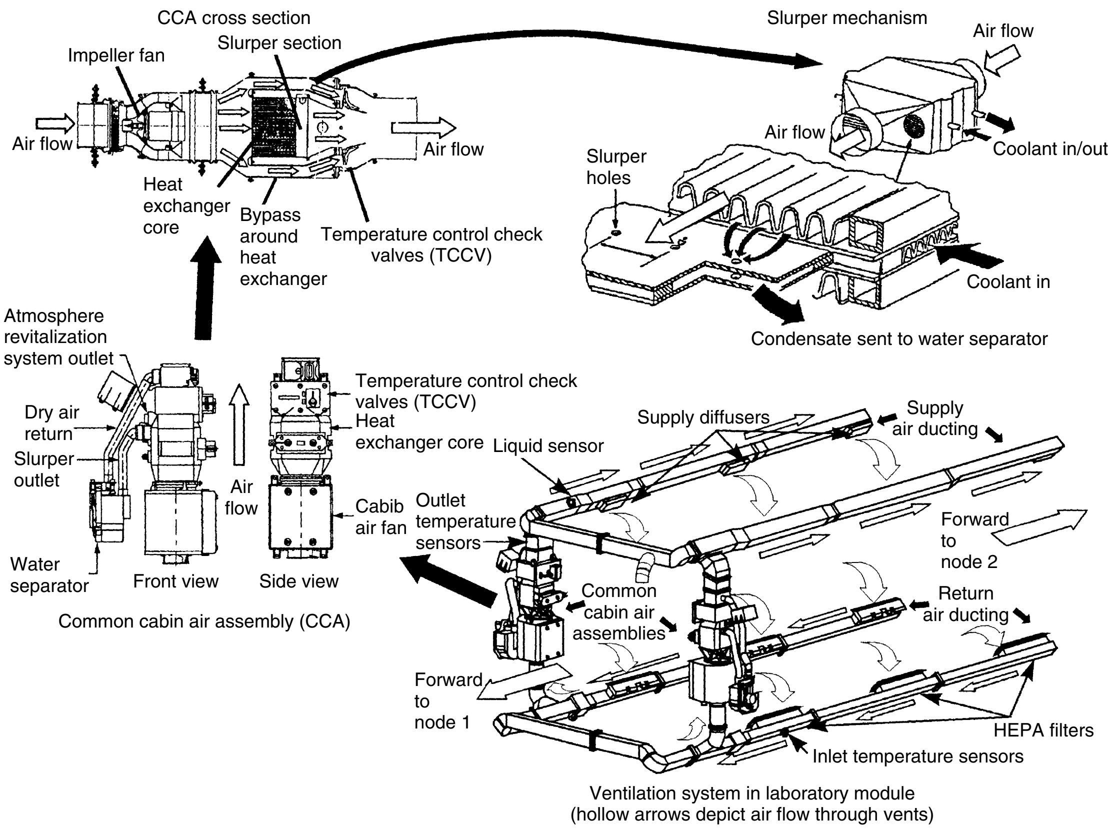


FIGURE 10-9 Diagrams of the international space station laboratory modules ventilation system, including details of the heat exchanger and the condensate collection systems. CCA, cabin air assembly.

in the American segment is collected in storage tanks, from which it can be vented overboard or manually carried to the water purification system in the Russian service module. With the addition of the habitation module, the American segment will receive its own water recovery system to augment the Russian environmental control systems.

Ventilation plays a critical role in the maintenance of uniform cabin temperature, humidity, and atmospheric composition. In the terrestrial gravity environment, the added buoyancy of warmed air allows objects to lose heat through convection. Convection also facilitates the atmospheric mixing necessary to maintain the homogeneity of its gaseous mixture. In the microgravity of space, these convection-based processes cannot occur. Spacecraft cabins must therefore incorporate ventilation systems to facilitate the transfer of atmospheric heat and humidity to the heat exchanger. The airflow of cabin ventilation must also be thoughtfully oriented to eliminate nonventilated regions, so that stagnant atmospheric pockets of decreased oxygen or increased carbon dioxide gas concentration do not develop. Fans, air ducts, and intake and diffuser grates are used to manage air exchange through the ventilation system. Lowering the atmospheric pressure decreases its gas density, requiring higher ventilation rates to achieve adequate atmospheric cooling. The ventilation fans in the low-pressure Apollo cabin were so loud that they could only be used intermittently. Figure 10-9 shows the overall layout of the ventilation system in the American Laboratory Module of the ISS, showing the tight integration of the subsystems used to filter, cool, and dehumidify the cabin air.

Fire Detection and Suppression

As was seen in the Apollo I fire, fires in spacecraft can be disastrous, so it is critical that the risk of a fire be minimized. The likelihood of a major fire can be reduced by minimizing atmospheric oxygen content and by using fire resistant materials, as well as by using ventilation systems that do not facilitate fire propagation. The longer a fire burns, the greater its damage potential. The uncontrolled fire of a perchlorate oxygen regeneration candle on board Mir apparently could have been a disaster (see Chapter 3 for details). Fortunately, it caused little actual damage and the smoke and other products of combustion were quickly cleared by the atmospheric revitalization system. Rapid fire detection is also essential. This proved problematic during another incident, when a smoldering fire in Mir's atmospheric revitalization system itself produced little smoke, but generated enough carbon monoxide to sicken the crew before it was detected and extinguished. In the event that a fire does occur, effective fire suppression methods must be available, along with appropriate cleanup implements. Such fire detection, suppression, and cleanup systems must also be compatible with the other life support systems within the spacecraft.

The sense of smell can identify smoke with a high degree of sensitivity and specificity and may be more reliable than artificial fire detection systems. Automatic fire detectors are needed to detect fire in unoccupied regions (such as avionics bays) and during crew sleep periods. In the space shuttle, unreachable avionics bays contain smoke and fire detectors connected to automatic fire extinguishers.

Fire suppression systems work by depriving a fire of oxidant, fuel, or heat, typically using water, foam, CO_2, or Halon. Because most fires in spacecraft would be related to electrical failures, water cannot be used. Foam and Halon have been used in American spacecraft, but can pose significant cleanup difficulties. Fire suppression in the American segment of the ISS uses handheld portable fire extinguishers that contain carbon dioxide, which require little cleanup. The fire extinguishers of the Russian segment contain a nitrogen-based substance that can be dispensed as a foam or liquid (24).

Extravehicular Activities

The history of spaceflight has proved the value of placing humans in spacesuits and allowing them to venture outside the protective confines of their spacecraft to perform EVAs. EVAs have included walking on the surface of the Moon, making critical repairs to space vehicles, and capturing satellites for repair. With the launch of the first modules of the ISS, the focus of EVAs has turned to space construction, as space-suited astronauts and cosmonauts work under difficult conditions to assemble the individual components of the large structure. The environmental and operational challenges of EVAs are slightly different from those of spacecraft life support systems and require unique solutions. To understand the relationship of EVAs to spacecraft atmospheric control systems, it is first necessary to understand the differences and similarities between spacesuit and spacecraft environmental control systems.

Spacesuits are essentially small autonomous life support systems that must sustain the astronaut for the duration of the assigned space walk—typically lasting 4 to 8 hours. To provide the required life support, spacesuits must perform nearly all the same life support functions required of complete spacecraft. Spacesuits must contain their wearers within an appropriately pressurized and breathable atmosphere and must protect them from thermal extremes, radiation, and micrometeoroid impacts. Fortunately, the short duration of EVAs limits the required size and complexity of spacesuit environmental control systems. Operationally, spacesuits must also provide sufficient mobility and dexterity to perform tasks and must be flexible enough so that the wearer does not become too fatigued to complete the tasks. These operational and technical restraints have a profound effect on what types of internal environmental conditions are feasible.

Flexibility and dexterity, the defining operational characteristic of spacesuits (after habitability), are determined by both the pressure gradient between the interior and the exterior of the suit and the spacesuit's design. The lower the pressure gradient, the more flexible and dexterous the spacesuit will be. Maximum spacesuit flexibility is achieved at minimum atmospheric pressure. When a 100% oxygen atmosphere is used, internal suit pressures as low as 21.5 kPa (3.1 psi or 160 mm Hg) can be easily tolerated and were used during the Mercury and Gemini programs. Internal pressure in Apollo and Skylab suits was increased to 26.6 kPa (3.85 psi or 200 mm Hg). The current American extravehicular maneuvering unit (EMU) has an operating pressure of 30 kPa (4.3 psi or 222 mm Hg), but can tolerate approximately 83 kPa (12 psi or 620 mm Hg) before rupturing. The Russian Orlon suit has the higher standard operating pressure (39 kPa, 5.7 psi, or 300 mm Hg). The Orlon suit can also be deflated to 27 kPa (3.9 psi or 202 mm Hg) for up to 15 minutes, allowing brief periods of increased suit flexibility and manual dexterity to perform more difficult tasks (20).

Wearers of early air-cooled spacesuits were plagued by overheating. The small internal volume, low internal gas density, low airflow, and tight fit of these spacesuits prevented adequate heat rejection from the interior. Replacing the air-cooling system with a liquid-cooling system improved this problem. Wearing a garment of water-containing coolant tubules close to the skin maximized heat rejection from the body, markedly improving the wearability of the spacesuits. The internal liquid-cooling garments in the Apollo spacesuits were capable of removing 147 W (500 BTU/hr), allowing astronauts to perform strenuous activities on the surface of the Moon without overheating.

The multilayer construction of the American EMU suit protects the wearer from the outside environment. Outer layers reflect solar radiation and resist abrasion, middle layers provide insulation and rigid structural support and protection, and inner pressure bladders retain the internal atmosphere. Electric glove warmers have been added to prevent frostbite when handling vacuum-cooled metal tools. The visor assembly filters out solar ultraviolet light and decreases the strong intensity of sunlight during daylight passes, preventing facial sunburns, as well as retinal damage. The entire EMU (with both spacesuit and its integral life support system) weighs approximately 130 kg (285 lb). In comparison, the Russian Orlon suit weighs considerably less (70 kg or 150 lb). The EMU self-contained oxygen supply and LiOH CO_2 scrubber can maintain habitability for 8 to 10 hours, if needed. On ISS, the LiOH canisters can be replaced with regenerable metal oxide CO_2 scrubbing canisters. Heat is rejected from the EMU using a water evaporator system.

Crewmembers performing EVAs are exposed to more hazards than are experienced on the interior of the spacecraft. Outside of the spacecraft, crewmembers are much more exposed to radiation, micrometeorite impacts, and thermal instability. Suit design must mitigate these risks as best as possible. Crewmembers also run the risk of being exposed to toxic propellants during an EVA, which could coat the outside of the suit with contaminants that could be carried back inside the vehicle on completion of the EVA. Procedures must be in place to prevent this potentially dangerous contamination of the interior of the spacecraft. There is also the potential for electrical shock resulting from the buildup of static electricity on the outside of the vehicle as it travels through space, making proper electrical grounding between the EVA crewmember and the spacecraft essential. Because of the atmospheric pressure changes associated with EVA, DCS poses a significant risk to spacewalking astronauts.

Decompression Sickness

When performing EVAs from the shuttle, Mir, or the ISS, the drop in atmospheric pressure from the standard internal pressure of the spacecraft (101 kPa, 14.7 psi, or 760 mm Hg) to the much lower operating pressure of a spacesuit (29.7 kPa, 4.3 psi, or 220 mm Hg) creates suitable conditions for the occurrence of DCS. DCS routinely occurred among the crewmembers of World War II aircraft, who experienced similar atmospheric pressure excursions to those experienced during space EVAs. DCS occurs when a drop in ambient atmospheric pressure causes the inert gas dissolved in bodily tissues (usually nitrogen) to exceed the saturation point at that pressure, causing the supersaturated gas to leave solution and to form gas bubbles. The formation of nitrogen bubbles in connective tissue can cause excruciating pain, leading to the agonized posturing of "the bends." Bubble formation within the central nervous system can cause cerebral ischemia and stroke-like symptoms, and bubbles within the pulmonary vasculature can lead to complete cardiovascular collapse and death (the "chokes"). DCS requires the presence of sufficient ambient partial pressures of inert gas. The 100% oxygen cabin atmosphere used during the Gemini and Apollo missions precluded the development of DCS during EVAs. Likewise, the partial pressure of nitrogen (P_{N_2}) of Skylab's atmosphere (9.7 kPa, 1.4 psi, or 72 mm Hg) was insufficient for the development of DCS (18).

DCS can be prevented during pressure excursions by (a) prebreathing 100% oxygen to purge nitrogen from bodily tissues before depressurization; (b) decreasing the starting atmospheric pressure so that the initial tissue nitrogen concentration is lower; and (c) raising the minimum atmospheric pressure experienced, so that the degree of tissue nitrogen supersaturation is lessened. Instituting these measures can prevent the development of DCS during EVAs.

When breathing 100% oxygen at ambient pressure, the lack of inspired nitrogen sets up a negative nitrogen concentration gradient between bodily tissues and the atmosphere, causing an efflux of nitrogen from the tissues. This efflux of nitrogen continues while 100% oxygen is breathed until virtually all tissue-dissolved nitrogen is removed. How quickly tissue denitrogenation occurs depends on the type of tissue and the amount of blood that flows through it. Tissue denitrogenation can be accelerated by exercising during the oxygen prebreathe. Exercise has been incorporated into the prebreathe protocols being developed for EMU EVAs from ISS, which can markedly reduce the required prebreathing time. It must be noted that denitrogenated tissues rapidly become resaturated when nitrogen is reintroduced to inspired air. Any interruption in the oxygen prebreathe can cause dangerous increases in tissue nitrogen concentration.

Lowering the ambient atmospheric pressure lowers the tissue nitrogen saturation concentration, so saturated tissues contain less nitrogen. Decreasing atmospheric pressure to lower initial tissue nitrogen levels can substantially shorten the duration of oxygen prebreathing required to prevent the occurrence of DCS. The night before a scheduled EVA, the space shuttle cabin is typically depressurized from 101 kPa (14.7 psi or 760 mm Hg) to 70.3 kPa (10.2 psi or 530 mm Hg), which decreases the duration of the required oxygen prebreathe from 4 hours down to 40 minutes (the cabin oxygen concentration is also enriched to approximately 23.5% so that the cabin P_{O_2} is maintained). Unfortunately, because the atmospheric pressure of the ISS is rigidly maintained at 101 kPa, this method cannot be used to safely shorten the duration of the oxygen prebreathe, unless EVA crewmembers "camp out" overnight in the airlock while depressurized to 70.3 psi (23). If sea-level pressure is maintained, a 4-hour traditional oxygen prebreathe is necessary to decrease tissue nitrogen concentrations to safe levels. Long preoxygenation periods consume significant amounts of 100% oxygen and negatively affect mission scheduling. Fortunately, research has shown that vigorous exercise performed during preoxygenation can increase the efflux of nitrogen from tissues, probably by increasing tissue capillary blood flow and the associated nitrogen washout. Such exercise prebreathe protocols can drop tissue nitrogen concentrations to safe levels with 2 hours or less of preoxygenation at standard atmospheric pressure. Because such decreases in prebreathe time improve the usage of available supplies and crew scheduling time, exercise has been incorporated into the prebreathe protocols being developed for EMU EVAs from ISS.

Decreasing the magnitude of the pressure excursion by raising the final atmospheric pressure decreases the risk of DCS by limiting the degree of potential tissue nitrogen supersaturation. In other words, if the spacesuit operating pressure is close enough to the ambient atmospheric pressure within the spacecraft, EVAs can be performed without breathing pure oxygen beforehand. As noted previously, the maximum operating pressure of EVA spacesuits is limited by the need to maintain adequate mobility and dexterity. The higher operating pressure of the Orlon suit (39 kPa, 5.7 psi, or 295 mm Hg) allows the Russians (who also accept a slightly higher level of DCS risk) use a 30-minute preoxygenation period. To date, no incidents of DCS have occurred in either the Russian or American EVA programs. The oxygen prebreathe could conceivably be eliminated if functional spacesuits with operating pressures above 62 kPa (9 psi or 460 mm Hg) could be developed.

When altitude-related DCS occurs, breathing 100% oxygen at ground-level atmospheric pressure is often sufficient to treat the condition. However, in cases of DCS that are refractory to ground level, hyperbaric oxygen therapy inside a hyperbaric chamber may be necessary to successfully treat the symptoms. An airlock with hyperbaric oxygen treatment capability was included in designs for the proposed space station Freedom, but this capability was not carried forward into the design of the ISS. Work has been done to develop a portable hyperbaric chamber for use on ISS in the event that a refractory case of severe EVA-related DCS occurs.

Water Storage, Recovery, and Management

To date, all inhabited spacecraft have contained supplies of potable water for the crew. Spacecraft must supply sufficient potable water to the crew for drinking, cooking, and personal hygiene, as well as for experimental projects. Humans consume an average of 2.3 kg (5 lb) of potable water per person per day for drinking and cooking (21). Significantly more water is required for personal hygiene activities, such as washing or showering. Potable water can be obtained from stored supplies or from fuel cells, which combine hydrogen and oxygen to produce electrical energy, generating water as a by-product. Fuel cells, used to supply the potable water in the Apollo command module and the shuttle, are a good water source for short-duration missions. Because they require large stores of hydrogen and oxygen, fuel cells are not used as a power source for longer missions, so needed water must be stored. Long-duration missions with several crewmembers require substantial supplies of potable water. When Skylab was launched, it contained adequate stored water to meet the needs of three crewmembers for its 171-day mission, totaling thousands of kilograms (14). Because the Russian Salyut and Mir space stations remained in operation for much longer, their stores of potable water were periodically replenished with water brought up in supply ships. The cost of launching and storing an adequate supply of water for missions of greater duration or crew size is prohibitive, making the recycling and conservation of potable water necessary. Wastewater recovery will be discussed in the next section.

Storing potable water (or any fluid) in space can be challenging. On Earth, gravity assists in retaining fluid, making open-topped storage tanks possible. Without gravity, liquids must be completely contained by their storage vessels to prevent them from escaping. Fluids cannot be easily removed from rigid-walled storage containers without gravity-assisted drainage. Flexible-walled containers work much better in space, because their shape and size can conform exactly to the stored volume of liquid, which allows fluid to be easily pumped in and out. A flexible storage bladder was used in the Mercury spacecraft. Flexible bladders sealed inside rigid metal tanks were used to store potable water in Russian Vostok, Voshkod, and Soyuz spacecraft (19). Mouth suction was sufficient to withdraw water from the tank. The Salyut and Mir space stations held potable water in larger metal tanks, which used a pressurized internal flexible bladder to deliver water. American spacecraft have a similar rigid tank design, but replace the bladder with a flexible bellows made of stainless steel. Flexible devices like bladders and bellows have limited life spans because their materials and designs are not as durable as those of rigid tanks. The movement and stretching of flexible components during filling and emptying further shortens their lifespan.

Stored drinking water in the Mercury capsules came directly from the municipal water supply of Cocoa Beach, Florida, as it was thought that the residual chlorine concentration was sufficient to suppress microbial overgrowth (20). Municipal water was also used during the slightly longer Gemini missions, although supplemental chlorine was added before launch to further prevent microbial overgrowth. Crewmembers added chlorine daily to the potable water produced by the fuel cells in the Apollo Command Module. The orange-flavored powder additive, Tang, was developed to mask the metallic taste of this fuel cell water, as well as to supply trace nutrients and minerals. Potable water in the lunar module came from storage tanks filled before launch, in which iodine was used instead of chlorine to avoid potential corrosion problems. Iodine was used as the biocidic agent of choice in subsequent American spacecraft. Skylab crewmembers periodically injected iodine into the water storage tanks, and check valves in the shuttle potable water supply (also generated by fuel cells) maintain iodine concentrations between 1 and 2 mg/L. Concerns developed that the daily intake of iodine associated with drinking this water could adversely affect the thyroid gland. As a result, an iodine removal system has been installed in the shuttle potable water supply loop to remove it immediately before dispensation.

The Russians use a slightly different approach to maintain water potability. Potable water is sterilized by boiling before transfer to the storage container in the spacecraft. Ionic silver is used to suppress microbial growth in stored water instead of chlorine or iodine. Electrolysis maintains ionic silver concentrations of 0.2 mg/L in the water supply systems of Russian long-duration spacecraft, such as the Salyut and Mir stations, as well as in the Russian ISS segment (25).

When potable water is used, it is not chemically altered or consumed, as oxygen is. Instead, water facilitates the transport of metabolic by-products and toxins out of the body. Water is excreted from the body in urine, feces, and vomitus, transporting various metabolic and microbial contaminants into the environment. Potable water used for personal hygiene and other purposes also contains a variety of biologic and chemical contaminants, such as dead skin, soap residue, and so on. Humans also excrete water into the atmosphere as respired water vapor and evaporated sweat, which also contain metabolic by-products. Once in the atmosphere, this wastewater vapor absorbs polar chemical (e.g., ammonia) contaminants that may have entered the atmosphere from other pollution sources. Atmospheric wastewater also adsorbs onto particulate matter suspended in the air. The atmospheric moisture that eventually condenses in the heat exchanger thereby contains a variety of impurities. Wastewater serves as a final collecting point for environmental contaminants from a host of sources.

Wastewater can be dealt with in a variety of ways. Most simply, it can be vented directly into space. Usually, wastewater is collected and stored until sufficient volume has accumulated, and then evacuated into space. Wastewater can also be directed through an evaporative heat exchanger to provide additional cooling. In long-duration spacecraft, in which water conservation is necessary, wastewater can undergo purification. A water sample's source (e.g., urine, solid bodily waste, hygiene and cooking water, and atmospheric condensate) determines the quantity and compositions of the contaminants it contains, which in turn determines the suitability of that fluid for recycling. Wastewater from sources that are relatively free of contaminants (such as condensation) may be returned to the potable water supply with minimal purification, but moisture collected from solid human waste may be heavily contaminated and may not be amenable to reprocessing at all. Collecting wastewater fractions from each source separately allows them to be individually processed, which conserves the maximum amount of water with less complex systems.

Historically, no American spacecraft contained wastewater-processing facilities. Wastewater from all sources, including atmospheric condensate, was vented overboard (14). Atmospheric condensate in the Apollo command module was sent through the evaporative heat exchange to assist in cabin cooling, although all wastewater generated in the lunar module was stored so that it did not contaminate the lunar surface. Wastewater was vented overboard from Skylab, as the sufficient potable water supplies onboard made recycling unnecessary. Because the space shuttle's fuel cells generate excess water supplies, wastewater is also vented overboard.

The Russian Salyut and Mir space stations were the first spacecraft to incorporate water recycling systems. Water recycling reduced the stations' dependence on fresh potable water launched from Earth. Wastewater from different sources was managed independently. Atmospheric condensate was collected and pumped into storage columns that contained ion exchange resins and activated charcoal and was then passed through various filters. Finally, after trace minerals were added, the purified water was to be used for showering. This system is reported to have recycled approximately 50% of the water used in Salyut 6, which reduced the required weight of stored water from 10.2 to 2 tons (19). In Mir, water from kitchen and hygiene usage was similarly purified and reused. Water was recovered separately from urine using vapor diffusion distillation. In this method, a wick was continually saturated with urine, which was heated to evaporate the moisture, leaving a residue of concentrated waste. The evaporated moisture was collected in a condensing heat exchanger and then used to supply water to the electrolytic oxygen generator. Because solid waste residue collects in the wick material, they must periodically be replaced with fresh wicks.

Efforts to reclaim atmospheric water in Mir for use in the shower met with problems. Cosmonauts noted that water reclamation system was not collecting as much moisture as expected. Subsequent analysis revealed that materials within the cabin were absorbing the moisture, and that some of these materials (such as sound and thermal insulation) held more than their own weight in water. This moisture-laden material was an ideal culture medium for bacteria. Autotrophic bacteria soon covered some areas in green slime. Wall insulation panels peeled away as heterotrophic bacteria consumed the adhesive that held them in place. Fans were used to dry the panels out and periodic wiping with bactericidal solution minimized the problem (20).

A similar water recovery system is present in the Russian ISS segment. Atmospheric condensate is collected using an air–fluid separator and pumped through decontamination columns containing ion exchange resins and activated charcoal. The purified water exiting the columns passes through a quality sensor that measures its electrical conductivity. If the electrical conductivity of water is low (which indicates acceptable purity), the water is returned to the potable water supply. Unacceptably high measurements of its electrical conductivity stop the flow and isolates the purifier until it can be serviced. Hygiene and cooking water is passed through the same system, and moisture from urine is reclaimed, as in Mir, to be used in electrolytic oxygen generation. As mentioned previously, the American ISS segment will not have its own water reclamation system until a habitation module with the ability to reclaim atmospheric moisture, urine, and hygiene water is installed.

Water quality monitoring is necessary to ensure that potability is maintained and that it is not contaminated with organic, inorganic, or microbial impurities. Russian and American spacecraft designers followed the dictum that as long as the quality of the stored water was verified preflight and proper steps were taken to prevent microbial colonization during the mission, water would remain in potable condition for the duration of the mission, making routine water quality monitoring unnecessary. During Skylab, water iodine concentrations were monitored using a simple colorimetric assay based on starch. Water temperature, pH, and salinity were monitored in Mir. Water samples from space station supplies have also been returned to Earth for analysis.

With longer duration missions, greater concern develops that water quality may degrade. Water quality can degrade in several ways. Chemical contaminants can enter the water supply through several mechanisms. Degradation of materials within the water management system can leach contaminants into the potable water supply. Chemicals leaking from systems that are in close proximity to water supply systems (such as coolant loops) may inadvertently cause contamination. Wastewater recycling introduces further methods of contamination. Failures of the purification system can allow wastewater pollutants or their partially degraded by-products to contaminate the water supply.

Spacecraft water supplies have become inadvertently contaminated. When the iodine removal system was first installed in the shuttle, crewmembers quickly noticed a strong chemical taste in the water. The foul taste was due to an organic compound, which had leached from the new iodine removal filter after being inadvertently generated when the filter was sterilized. The compound was found in measurable quantities in crewmembers' urine for several days postflight. Fortunately, crewmembers were able to taste the chemical in the drinking water and switch to other stored water, which limited their chemical exposure. If the chemical had been tasteless, they would have been unaware of it and they would have continued drinking the contaminated water.

Monitoring for every potential water contaminant is difficult. However, tracking of a few key parameters, such as water pH, conductivity, and total organic carbon and iodine concentration, can provide a general assessment of water quality and the functioning of the water purification system. Such monitoring is adequate to verify that the integrity of the water storage and purification systems has not been compromised. In the Russian ISS segment, the electrical conductivity of water coming from the water reclamation purifiers is measured real time. Any increases in the electrical conductivity of the water, which can indicate the presence of contamination, can shut down the system.

More in-depth analysis, such as mass spectroscopy can be used to identify individual water contaminants, which can help identify their source. During future long-duration missions far from Earth, it may be impossible to return samples to Earth for analysis or to receive supplemental water supplies. Because of this, it is critical to develop water quality monitoring and maintenance systems that reliably detect and manage contamination of the water supply. Experience gained in this area from the ISS will be invaluable. Therefore, on-orbit spectroscopic water analysis capability is being planned.

Monitoring of microbial organisms in the water supply is also of high importance. Failure of microbial suppression mechanisms in the water supply system could result in microbial colonization, leading to concentrations of microorganisms in potable water that could adversely affect crew health and safety. Fortunately, biologic monitoring of shuttle water supplies has revealed no significant fungal or bacterial contamination (23). Automatic monitoring systems that could detect microorganism contamination of the water supply would be helpful during the long-duration missions using recycled water, but adequately sensitive detection systems are difficult to design. Detecting waterborne microorganisms at concentrations of 0 to 10 colony forming units (CFU) per 100 mL is difficult, time consuming, and requires large amounts of equipment and growth media and can generate significant amounts of biohazard waste. Microorganism concentrations will be monitored in the water supply of the ISS, which may hopefully facilitate the development of more advanced microbial detection systems.

In the future, biologic systems may not only be used to provide water and atmospheric purification but may also serve as sensitive indicators of environmental quality. Similar systems have been used before. Canaries brought into mines were more sensitive to toxic gases than humans. Their demise warned miners of the potential buildup of toxic gas in the mine shafts. Scientists have theorized that the recent global decimation of amphibian species indicates subtle degradation of environmental quality. These biologic principles, along with the fast pace of biotechnology advancement, could be used someday to design extremely sensitive biologic environmental monitoring systems.

Human Waste Management

Because the Mercury missions were of such short duration, no provisions were made for human waste during these missions until Alan Shepard urinated in his spacesuit on the launch pad. For subsequent missions, collection devices for human waste were supplied. Feces were collected and stored in bags. After use, chemicals were mixed with the feces to prevent microbial gas formation from exploding the bags. Urine was collected separately and vented overboard. A commode was used on Skylab to collect, dehydrate, and store feces for analysis back on Earth. (The samples are still stored at Johnson Space Center.) The shuttle commode uses a complex centrifugal mechanism to collect, dehydrate, and store fecal material until it can be removed on return to Earth. It was also designed to accommodate both male and female users. The complexity of this system can occasionally affect its reliability, so backup fecal storage bags are also provided.

The Russians use a different approach to manage human waste (19). Russian spacecraft have always been more tightly sealed than American spacecraft, so waste material is not usually vented directly overboard. The human waste collection system found in Vostok, Voshkod, and Soyuz used an airstream to collect both urine and feces, directing waste material to a common storage tank. Urine and feces were collected separately in the Salyut and Mir stations. Fecal material was collected and stored in hermetically sealed containers, which were ejected from the station weekly and replaced with fresh canisters. Urine was separately collected and disposed of. Mir had a similar system but instead of disposal, urine was distilled to collect water to be used in electrolytic oxygen generation. The Russian commode design accommodates both males and females.

The ISS toilet, located in the Russian service module, is very similar to the Mir design. Solid waste is collected in a porous bag that allows air and liquid waste to be pulled through into the air–liquid separator. Once used, the waste bag is sealed and stored within the commode until disposed of. The separated waste liquid is sent on for further filtration and processing, and the contaminated air in the toilet passes back through the atmospheric purification system. Eventually, the American segment will have its own toilet facilities.

Food Preservation, Storage, and Preparation

Along with the necessary environmental conditions, humans in space must also be provided with adequate nutrition if they are to survive for any length of time. Food must provide proper nutrition so that adequate physical and cognitive task performance ability is maintained. Food also plays an important psychologic role in spaceflight. Providing palatable and enjoyable food is critical in maintaining crew morale and can facilitate social interaction at mealtimes, which are often the only times that crewmembers are able to relax together.

Food brought to space must be carefully packaged to minimize stowage volume and must be preserved so that it may be stored at room temperature without decaying in quality. The food stowage and preservation methods must allow food to be prepared quickly and easily with a minimum of equipment and must generate little waste material. Finally, food must also be of a consistency that allows it to be eaten in microgravity with minimal mess and inconvenience. In general, flaky or crumbly foods and foods that do not stick together well are avoided.

During the Mercury program, there were concerns that astronauts would not be able to swallow in space. Food that was easy to swallow and digest and that could be delivered by tubes inserted through the helmet faceplate was provided. Foods consisted of pureed meats, fruits, and vegetables in collapsible containers. Freeze-dehydrated foods were provided on later missions. During the Gemini missions, this menu was extended for more variety. Most foods were dehydrated to minimize stowage and extend shelf life, some of which could be rehydrated before consumption. These foods were also used during early Apollo missions; crewmembers could eat the foods with their fingers or suck the foods out of the containers through tubes. During later Apollo missions, some dehydrated foods were replaced by thermostabilized foods, which contained a more normal moisture content and were more palatable to the crews. Irradiated foods were also first used during Apollo. The menu was further expanded during Skylab, when a mixture of rehydratable, thermostabilized, precooked frozen, and ready-to-eat food was included. A small galley was available to rehydrate and heat foods. Food was packed in collapsible containers and aluminum cans. Because detailed metabolic studies were performed during Skylab, food nutritional content was carefully measured, and food consumption was carefully measured.

In contrast to earlier missions, foods on the shuttle predominantly are commercially available products, giving a large variety of thermostabilized, rehydratable, intermediate-moisture, and ready-to-eat foods. Dehydrated foods that can be rehydrated using the shuttle galley water are used whenever possible. Foods are usually stowed in flexible pouches that minimize trash volumes. Crewmembers meet with dietitians to plan the complete menus before their missions and are given a wide variety of choices. One particular crewmember always selected the favorite food item (shrimp cocktail) as the main course for every meal during the missions.

Russian experience with food in space is similar to that in American spacecraft. Pureed foods were supplied during early Vostok missions, and gradually a wider variety of foods and food preparation techniques were added. On Mir, food consisted of rehydratable items and canned goods that could be heated in a food warmer. Fresh fruits and vegetables were brought up in Progress supply modules for added variety.

Providing food for the ISS combines Russian and American space culinary experience and will use food systems developed during the shuttle and Mir programs (9). The galley, located in the Russian segment, provides areas for food storage, preparation, consumption, and trash disposal. Food warmers are compatible with Russian and American supplies, and potable water dispensers offer ambient temperature water for drinking or hot water for food rehydration. Eating utensils allow crewmembers to eat without using their fingers. Most foods can be stowed at ambient temperature (freeze-dried or thermostabilized). Fresh foods brought up from the ground occasionally add variety.

Future long-duration missions beyond LEO will require very large stores of food. Great care will need to be taken to ensure that adequate amounts of nutritious, palatable food are available and that the shelf life is adequate for the entire mission. This may necessitate the actual growing of food during the mission, using plants to regenerate food from metabolic by-products. Such food production systems would also integrate with other biologic life support systems, offering levels of mass loop closure not seen with nonbiologic systems.

Personal Hygiene Equipment

Personal hygiene plays an important role in maintaining human performance. Maintaining personal hygiene suppresses microbial growth on bodily surfaces, decreasing the possibility that these organisms will cause disease. Periodic cleansing of the skin also collects and removes excess skin cells, which would otherwise be shed into the cabin atmosphere. Personal hygiene sufficient to limit body odor is obligatory in some cultures, but less important in others. Hygiene issues become important when international crews spend long periods in close contact because maintaining acceptable levels of personal hygiene is also important to crewmember morale. Basic personal hygiene includes such activities as washing the body and hair and brushing the teeth. For longer missions, shaving, showering, and laundering clothes is desirable.

Early space missions were of such short duration that personal hygiene equipment was not included. Basic hygiene activities were soon supported as mission duration increased. On Skylab, astronauts were able to wash themselves, brush their teeth, and even shave. Attempts were made on both Skylab and Mir to include a shower (19). Although these devices did function, they required unacceptable amounts of time to set up and operate. In general, operationally effective facilities for showering, hair washing, and laundry have not been developed. During shuttle missions, sponge and towel baths are the most effective method of bodily cleansing, and a non–water-based shampoo has been found effective. These methods are also used on the ISS. For future long-duration missions, acceptable solutions to these personal hygiene challenges will have to be found.

Communication Systems

The ability to communicate with the Earth is absolutely essential. More than just providing a means to relay information, requests, and instructions back and forth, communication systems link space travelers with the terrestrial environment, keeping them in touch with their loved ones back home. In the early days of spaceflight, communication was spotty at best. Communication was limited to the brief periods when the spacecraft passed overhead, unless relay stations in remote locations around the globe were set up. Now, satellite communication systems have minimized the periods of communication blackouts to only a few minutes per orbit for the space shuttle. Russian communication systems are often limited to periods when the spacecraft flies over Russian territory. In the ISS, the high-bandwidth communication system allows the transmission of large amounts of encrypted and unencrypted data. Traveling to distant destinations will cause further communication problems. Time delays will hamper communication between the Earth and distant spacecraft. More powerful and sophisticated communications equipment will be necessary to meet these challenges.

Cabin Volume and Habitability

Once basic life support requirements have been fulfilled, other characteristics of the environment must be considered to make it conducive to human habitability. The volume and layout of the spacecraft cabin must be suitable for the number of crewmembers it is expected to hold. Early spacecraft were quite small. The Mercury capsule contained 1.56 m^3 (55 ft^3) of habitable space, much of which was taken up by equipment, making freedom of movement impossible. Likewise, the Gemini capsule contained even less space per person than Mercury, just 2.26 m^3 (80 ft^3) of space for two astronauts. The Russian Vostok capsule had the least space of all, with a habitable volume of only 2 to 3 m^3 (~6.5–10 ft^3)! Voshkod and the later Soyuz were larger and able to carry three crewmembers. Soyuz had a habitable volume of approximately 10 m^3 (353 ft^3). Incidentally, it was only once cabin volumes became large enough for crewmembers to move around that motion sickness related to the physiologic adaptation to microgravity became apparent. The Americans did not notice motion sickness until they began using the larger Apollo spacecraft, whose command module (habitable volume 5.9 m^3 or 210 ft^3, minus 0.25 m^3 or 9 ft^3 taken up by the contained life support system) and lunar module (habitable volume 4.5 m^3 or 159 ft^3) contained a habitable volume very similar to the Soyuz. In comparison, the multilevel cabin of the American space shuttle contains 74 m^3 (2,615 ft^3) of habitable volume and can typically carry seven crewmembers. The habitable volume of the shuttle can be further increased by attaching Spacelab and Spacehab modules to the airlock, providing further life-support structures that ride in the shuttle cargo bay.

Because of their long-duration missions, designers of space stations have made them as large as possible. The Russian Salyut space stations contained roughly 100 m^3 (3,500 ft^3). Skylab, the largest single-unit spacecraft flown to date, contained 361 m^3 (12,750 ft^3) of habitable volume, yet was designed for only three crewmembers. The Mir Space Station complex, consisting of a core module (habitable volume roughly 150 m^3 or 5,300 ft^3) and seven additional modules, including an American airlock adapter, barely reached the volume of Skylab. With a planned internal habitable volume of 1,218 m^3 (43,000 ft^3) when complete, the ISS will be largest human-made space structure ever.

For long-duration missions, adequate habitable space is extremely important because it affords crewmembers some small element of privacy. The Russian Salyut and Mir space stations contained two small staterooms for crewmembers, leaving extra crewmembers to find small nooks for themselves. Occasionally, sleep stations were flown on the space shuttle, which crewmembers report offered them welcomed periods of privacy. The Russian service module of the ISS also contains two small private staterooms. Further private space will not become available until a habitation module is installed. Future long-duration spacecraft will need to be of sufficient habitable volume to include private space for all crewmembers, which can be instrumental in facilitating the diffusion of interpersonal tension.

Along with habitable volume, how that volume is divided and decorated can strongly influence how living and working in that environment is perceived. American spacecraft designers have typically chosen rather sterile, white interiors for spacecraft cabins. Crewmembers have found them to be quite habitable. The Russians have gone much further in experimenting with spacecraft interior design. In the Salyut and Mir space stations, interior decor was selected that might provide a "homey" quality to the environment that would not be psychologically oppressive to the cosmonauts during long-duration missions. Interestingly, they also gave the stations a strong floor-to-ceiling orientation. Interior surfaces were painted in soft pastels. In Mir, carpeting was added to some surfaces to promote the sense of a normal home or office space. Both American and Russian interior design concepts are being used in the ISS. This experience will help in the design of future long-duration space habitats.

For spaceflights lasting more than a few hours, it is important to provide an environment that is conducive to sleep. If crewmembers are unable to achieve adequate sleep, their task performance ability will degrade within a few days. Noise reduction is essential in maintaining a proper sleep environment. Although the various pumps, fans, and compressors inside spacecraft are critical for the maintenance of the habitable environment, they are often loud enough to interfere with sleep. If the cumulative noise level is sufficient, hearing loss can occur with chronic exposure. Ventilator fans in the Apollo spacecraft were so loud that they were only run intermittently. Spacecraft designers face the challenge of selecting the quietest equipment that can perform the desired function. Insulation can also be effective if further sound reduction is necessary. Astronauts note that the space shuttle cabin systems are reasonably quiet. Some regions in the ISS are fairly quiet, but some modules can be loud enough to make the use of noise protection devices advisable. Cabin noise will become even more important as the durations of future space missions increase, so that the adverse physiologic and psychologic effects of long-term noise exposure can be avoided.

Cabin lighting must provide adequate illumination for task performance during working hours. Artificial lighting must be used because ambient solar lighting is problematic. Unfiltered solar lighting is quite intense and can cause significant retinal and skin burns with only a few seconds' exposure. Even when filtered, spacecraft in orbit experience rapid light to dark cycling and changes in vehicle orientation relative to the Sun make ambient light an unreliable source of illumination. Despite the disadvantages of outside lighting, windows are an important feature of inhabited spacecraft. They allow crewmembers to monitor the outside of their vehicles, which is essential when EVAs are taking place, such as spacecraft docking, cargo handling, and space walks. In LEO, observing the Earth is an absorbing and entertaining pastime that can provide useful scientific data. However, because there is often little to see out of windows during long-duration missions away from the Earth, the drawbacks of having them may outweigh the benefits.

Full-spectrum artificial white light provides the best illumination and is subjectively the most pleasant. The ability to dim or extinguish cabin lighting is also desirable because humans function optimally when provided with a dark environment in which to sleep. On occasion, double-shift work schedules have been used during shuttle missions, so sleep stations have been used to provide an isolated, dark sleep environment for off-duty crewmembers. When single workshifts are used and everyone sleeps at the same time, crewmembers often prefer to put shades over windows so that their sleep is not disturbed by the frequent sunrises and sunsets. In some cases where dimming the cabin interior is not possible, crewmembers resort to wearing eyeshades. The interior lighting in the ISS provides full-spectrum light of adequate luminosity to support work activities and can be dimmed or extinguished as desired. Battery-powered backup lights are also available should total power loss to the module occur.

Providing entertainment is also critical because boredom during long missions can lead to depression and interpersonal difficulties. Apart from looking out the window, other activities are needed. Astronauts have often brought along recordings of their favorite music. Mir contained a library of more than 400 books. On the ISS, the high-bandwidth communications system can provide crewmembers with current events, music, and even videos and movies. Future spacecraft will benefit from the rapid advances taking place in computer and information technology.

Along with the essential environmental conditions provided by the life support and safety equipment detailed previously, spacecraft habitable environments must also be equipped with a further array of equipment that helps to maintain crewmembers in optimal health and condition. Exercise equipment is required so that musculoskeletal strength and cardiovascular fitness are maintained so that crewmembers are able to do their jobs and return to Earth without marked difficulty. Medical equipment and supplies must be adequate to treat routine illnesses, as well as to stabilize and maintain more severely sick or injured crewmembers until they can be returned to Earth for further care.

Future Directions in Spacecraft Habitable Environments

Many of the previous sections have discussed potential and necessary developments that will facilitate future long-duration missions. In general, such missions will require much greater mass loop closure, which will require significant advances in regenerable life support systems. Life support systems will need to efficiently convert both metabolic by-products and other environmental contaminants back into usable forms, such as pure oxygen, water, and even food. In all likelihood, the advanced systems needed for these tasks will incorporate biologic processes and systems. Along with these systems comes the need for much more sensitive monitoring of environmental conditions, as well as the capacity to correct perturbations within the environmental control systems.

On a further note, experience with the ISS may indicate that for long-duration exploration-class missions some type of artificial gravity will be required to maintain adequate crew health and fitness. Prototype systems have already been developed that use centrifuges to generate pseudogravity. Large-scale centrifuges may be incorporated into the life support systems in future spacecraft. The artificial gravity generated by such systems would not only provide physiologic benefits but would also facilitate the use of simpler gravity-dependent life support and personal hygiene systems.

CONCLUSION

Environmental conditions in space are much harsher than those experienced on Earth and are not conducive to human survival. However, life support systems have been developed that allow humans to survive in space. The longer the duration of the spacecraft's voyage, the more complex these systems become. Spacecraft life support systems must maintain environmental conditions without wasting precious supplies. Over time, life support systems have become much more capable, but much greater efficiency will be necessary to make human exploration of distant planets possible. The ISS highlights the challenges of life support system integration and implementation. Experience gained from this ambitious endeavor will be essential for the development of future spacecraft habitable environments.

ACKNOWLEDGMENTS

The author would like to acknowledge Sheri Dunnette, for significant technical and moral support in the preparation of this chapter; Dom Del Rosso, Roger Billica, Jeff Jones, and the many others at Johnson Space Center who reviewed its content; and Terry Johnson for assistance in graphics preparation.

REFERENCES

1. Van Beckh HF. The space medicine branch of the Aerospace Medical Association. *Aviat Space Environ Med* 1979;50:513–516.
2. Waligora JM, ed. *The physiologic basis for spacecraft environmental limits.* (NASA RP-1045). Washington, DC: NASA Scientific and Technical Information Branch, 1979.
3. Lundquist CA, ed. *Skylab's astronomy and space sciences.* (NASA SP-404). Washington, DC: US Government Printing Office, 1979.
4. Strategic program plan for space radiation health research. Presented at the *9th Annual Space Radiation Health Investigators' Workshop*, Loma Linda, 1998.
5. Wilde RC, ed. Radiation issues. In: *Extravehicular crewman work system (ECWS) study program*, *Executive summary*. (NASA SP-04J77). Vol. 1. Windsor Locks: Hamilton Standard, 1980.
6. Nachtwey DS, Yang TC. Radiological health risks for exploratory class missions in space. *Acta Astronaut* 1991;23:227–231.
7. Simonsen LC, Nealy JE, Townsend LW, et al. *Radiation exposure for manned Mars surface missions.* (NASA TP-2979). Hampton: Langley Research Center, 1990.
8. The National Research Council Committee on Toxicology. *Spacecraft maximum allowable concentrations for selected airborne contaminants*. Vol. 4. Washington, DC: National Academy Press, 2000.
9. *International space station medical operations requirements documents*. (NASA SSP-50260, Revision A). Houston: 2000; JSC internal reference document.
10. National Council on Radiation Protection. *Guidance on radiation received in space activities.* (NCRP Report No. 98). Washington, DC: Scientific and Technical Information Office, 1989.
11. National Council on Radiation Protection. *Guidance on radiation received in space activities.* (NCRP Report No. 98). Washington, DC: Scientific and Technical Information Office, 2001.
12. *Nutritional requirements for international space station missions up to 360 Days*. (JSC 28038). Houston: 1990; JSC internal reference document.
13. Ruppe HO. *Introductions to astronautics*, Vol I and II. New York: Academic Press, 1966.
14. Popma DC. Environmental control system development for manned spacecraft—1960–1973. (ASME 74-ENAs-50). Paper presented at the *Intersociety Conference on Environmental Control Systems*, Seattle, 1974.
15. *Report of the Apollo 204 [Apollo 1] review board.* Washington, DC: US Government Printing Office, 1967.
16. Johnston RS, Dietlein LF, Berry CA. *Biomedical results of Apollo.* (NASA SP-368). Washington, DC: Scientific and Technical Information Office, 1975.
17. Hopson GD, Littles JW, Patterson WC. *Skylab environmental control and life support systems.* ASME Paper 71-AV-14. San Francisco: American Society of Mechanical Engineering, 1971.
18. Morgenthaler G, Fester DA, Cooley CG, et al. An assessment of habitat pressure, oxygen fraction and EVA suit design for space operations. *Acta Astronaut* 1994;32(1):39–50.
19. *Soviet space programs, 1981–1987, part I*. Washington, DC: US Government Printing Office, 1988.
20. Wieland P. *Designing for human presence in space: an introduction to environmental control and life support systems.* (NASA RP-1324). Huntsville: NASA Marshall Spaceflight Center, 1994.
21. Eckart P. *Spacecraft life support and biospherics.* Torrance: Kluwer/Microcosm, 1996.
22. Parks KL, Bridges MC. *Trace contaminant control system (TCCS)*. (NASA JSC-36331). Houston: JSC internal reference document, 1998.
23. Nicogossian AE, Huntoon CL, Pool SL. *Space physiology and medicine*, 3rd ed. Malvern: Lea & Febiger, 1993.
24. *International space station familiarization.* (NASA JSC TD9702A). Houston: 1998; JSC internal training document.
25. *International space station Russian segment life support system (LSS ISS) study guide*. Star City: 1997; Russian Space Agency internal training document.

RECOMMENDED READINGS

Eckart P. *Spacecraft life support and biospherics.* Torrance: Kluwer/Microcosm, 1996.

Johnston RS, Dietlein LF, Berry CA. *Biomedical results of Apollo.* (NASA SP-368). Washington, DC: Scientific and Technical Information Office, 1975.

Lane HW, Schoeller DA, eds. *Nutrition in spaceflight and weightlessness models.* New York: CRC Press, 2000.

Nicogossian AE, Gazenko OG, eds. *Space biology and medicine.* Washington, DC: AIAA, 1994.

Nicogossian AE, Huntoon CL, Pool SL. *Space physiology and medicine*, 3rd ed. Malvern: Lea & Febiger, 1993.

Waligora JM, ed. *The physiologic basis for spacecraft environmental limits.* (NASA RP-1045). Washington, DC: NASA Scientific and Technical Information Branch, 1979.

Wieland P. *Designing for human presence in space: an introduction to environmental control and life support systems.* (NASA RP-1324). Huntsville: NASA Marshall Spaceflight Center, 1994.

CHAPTER 11

Pilot Health and Aeromedical Certification

Robert R. Orford and Warren S. Silberman

The difficulty lies, not in the new ideas, but in escaping the old ones, which ramify, for those brought up as most of us have been, into every corner of our minds.

—John Maynard Keynes

FACTORS INFLUENCING AIRCREW HEALTH

Practitioners of clinical medicine are trained to prevent, diagnose, and treat conditions that alter a patient's physiology in a normal environment. Practitioners of aerospace medicine must also understand how both normal and abnormal physiology may be affected by the many physiologic stresses of flight, such as acceleration, air pressure changes, hypoxia, heat stress, and circadian dysrhythmia. Aircraft and life support systems are designed to counter these threats. Yet, even with these countermeasures, performance and safety are occasionally impaired due to man's inability to fully accommodate to the flight environment. Consequently, both civilian and military aviation organizations continue to seek healthy, fit aircrew members whose constitutions are most adaptable and resilient with respect to the physiologic stresses of flight. Major environmental and endogenous factors influencing aircrew health are summarized in Table 11-1.

Environmental Factors

Gravity/Acceleration

The effects of gravity and acceleration on the cardiovascular, visual, vestibular, and other systems are reviewed elsewhere in this text (see Chapter 4). Because $+G_z$ and $-G_z$ forces primarily affect the cardiovascular system, it is extremely important that individuals who fly G-inducing aircraft are assessed for cardiovascular and vestibular disease and know how to use countermeasures effectively.

Aircraft Design/Ergonomics

Whereas civilian aircrew may make due with shirtsleeves and a slender headset for communications, aircrew in military aircraft are protected from head to toe, with gear including a 1- to 2-kg helmet with night vision devices (NVDs) attached, a life-preserver-torso harness unit, Nomex flight suit and gloves, an anti-G suit, and flight boots. Additional heavy and bulky Capstan suits are used for high-altitude missions (1). This life-support and mission-critical gear is physiologically demanding in terms of its bulkiness, heat retention properties, and especially, the weight and forward center of gravity imposed by the

TABLE 11-1

Factors Influencing Aircrew Health

Environmental	*Endogenous*
Gravity/acceleration	Aging
Aircraft design/ergonomics	Fatigue
Hypoxia	Psychosocial stress/poor communication
Heat stress	Circadian dysrhythmia
Air pressure changes	Menses
Noise and vibration	Tobacco, alcohol, and drug use
Radiation/lasers	Self-medication
Cabin air quality	Sedentary lifestyle
Infectious diseases	Nutrition
Hazardous cargo	Acute and chronic illness

helmet-NVD-mask complex on the cervical spine and soft tissues. High levels of neck muscle activation and co-contraction occur during acceleration and aerial combat maneuvers (2). Back seat occupants are at risk of acute soft tissue neck injury from unexpected acceleration. Numerous authors have addressed aircrew ergonomic issues (3–6) and their prevention, including neck strengthening exercises, preflight neck warm-up exercises, and eliminating/limiting head movement while pulling Gs.

Hypoxia

Most aircraft do not pressurize to sea level pressure while airborne. Whereas healthy crewmembers can tolerate mildly hypoxic environments, the same is not true for individuals with reduced blood oxygen carrying capacity resulting from cardiac or pulmonary disease. Even at normal cabin altitudes of commercial aircraft (6,000–8,000 ft), they may develop hypoxic symptoms and require supplemental oxygen.

Heat Stress

Cockpit temperature and humidity are reasonably well controlled in commercial aircraft; however, the same cannot be said for many types of military aircraft. Heat stress is particularly threatening to military crews operating in tropical or desert climates. Long-term engineering solutions include installation of cockpit and cabin air conditioning systems, as well as development of efficient personal cooling garments. The latter may be of particular importance for heavily encumbered aircrew operating in nuclear-biologic-chemical protective gear. Aircrew operating in such environments must also maintain adequate hydration both before and during flight (see also Chapter 7).

Circadian Dysrhythmia (Jet Lag and Shift Lag)

Long-haul commercial and military aviators may find sunlight and activity hours drastically altered. It is not unusual for such aviators to traverse eight or ten time zones, which affect their alertness and performance (jet lag). Desynchronization may also occur as a result of working variable shifts (shift lag). With either jet lag or shift lag, operational, family, or social activities during daylight hours hamper recovery sleep. Preventive and mitigating strategies are discussed elsewhere in this volume (see Chapter 23).

Air Pressure Changes

Barometric pressure decreases with altitude from a sea level value of 760 mm Hg to the vacuum of space. Without adequate protection, flight crewmembers are not only at risk of becoming hypoxic but also of developing decompression sickness with increasing altitude. Crewmembers at altitude may also experience barotrauma resulting from pressure differentials between body cavities (e.g., sinus, middle ear, diseased teeth, and gastrointestinal tract) and the ambient air. Sinus block and middle ear block are most likely to induce pain, most likely during descent (see Chapter 18). This may distract, or even incapacitate, an affected crewmember. Pressure-equalizing earplugs do not appear to prevent barotrauma on descent from 8,000 ft cabin altitude.

Noise and Vibration

Noise from an aircraft engine, jet, or propeller may affect communication, and may cause acoustic trauma or hearing loss, particularly with prolonged exposure (see also Chapter 5). Noise levels up to 130 dB have been measured in the flight line environment (2). Both aircrew and ground crew working near the flight line are at risk. Hearing conservation programs are therefore used to identify and contain flight line noise where feasible, and to provide hearing protection (earplugs or earmuffs for ground personnel; earplugs, snugly fitting headphone or helmet, and/or noise canceling earphones for aviators) to lower the time-weighted average exposure to permissible levels. Vibration may contribute to back pain among aviators especially in rotary wing aircraft operations.

Ionizing Radiation

The principal source of exposure to ionizing radiation in the flight environment is galactic cosmic radiation in the form of neutrons and γ rays. Cosmic ionizing radiation increases with flight altitude and with proximity to the poles. Exposure can damage chromosomes and may increase the risk of cancer and adverse reproductive outcomes. Nuclear cataracts have also been attributed to ionizing radiation exposure. The International Commission on Radiation Protection and Measurement (ICRP-60) limit for occupational exposure is 20 mSv/yr, averaged over 5 yr. The upper limit for unborn children is 22 mSv exposure to the surface of the pregnant woman's abdomen over the period of gestation. Effective annual doses absorbed by nonpregnant crewmembers are well within these limits, ranging from 2 mSv for the least exposed routes, to 5 mSv for those more exposed. Female crewmembers will need to limit their flight time if they fly during pregnancy. Flight at altitude during increased solar flare activity may expose aircrew to increased doses. The Federal Aviation Administration (FAA) monitors solar activity and is capable of alerting flight crews should abnormal levels exist, and provides a tool to estimate galactic cosmic radiation received in flight (see also Chapter 8).

Nonionizing Radiation

External sources potentially affecting aviator health include electromagnetic frequency (EMF) radiation emitted by aircraft electrical equipment, light in the ultraviolet (UV) portion of the spectrum, laser beams, and radio frequency sources such as radar. Aircraft window glass and acrylic are opaque to UV radiation at wavelengths less than 320 and 380 nm, respectively. This protects aircrew from all but UV-A (320–400 nm), a significantly less harmful form of UV radiation than the shorter wavelength (290–320 nm) UV-B. Diffey and Roscoe measured UV doses on 18 flights on

Boeing 737s and 767s from the United Kingdom to the Mediterranean. Results verified the assumption that only negligible exposure occurred. Attenuation of radar in the air and the fact that the cockpit itself serves as a "Faraday cage," a structure made of conducting material that impedes the passage of electromagnetic radiation, both serve to shield aviators from excessive exposure to radar. Cockpit sources of nonionizing radiation (NIR) include the instrument panel and headset/helmet communication system.

Lasers

Lasers have served the military for years as range finders and target designators. Those in the visible and near infrared range such as the commonly used 10,646 nm Nd:YAG laser may cause retinal damage. Lasers pose a safety hazard for both ground personnel in proximity to the beam and for aviators (ground to air laser illumination). Laser glare may interfere with critical phases of flight, leading to loss of situational awareness, flash blindness, and afterimages similar to those induced by exposure to a high-intensity flash. This may impair aircrew eyesight for a period long enough to cause a mishap. Permanent blindness is a theoretic possibility. Regulations requiring permits for commercial use of lasers in close proximity to airspace have been promulgated to protect aircrew from civilian lasers. In the United States, laser airspace guidelines can be found in FAA Order 7400.2 (Revision "F" as of August 2006), Part 6, Chapter 29 "Outdoor Laser Operations." Bright light airspace guidelines are in Chapter 30 "High Intensity Light Operations".

The FAA has established airspace zones around airports: The laser-free zone extends immediately around and above runways. Light irradiance within the zone must be less than 50 nW/cm^2. The critical flight zone covers 10 nautical miles around the airport; the light limit is 5 μW/cm^2. The optional sensitive flight zone is designated by the FAA, military or other aviation authorities where light intensity must be less than 100 μW/cm^2. This might be done for example around a busy flight path or where military operations are taking place.

Military organizations, such as the United States Air Force (USAF), issue aviators laser protective spectacles and visors effective against several wavelengths. The use of tunable multispectrum laser weapons will pose an additional challenge. The International Civil Aviation Organization (ICAO) has published a *Manual on Laser Emitters and Flight Safety*.

Cabin Air Quality

The most obvious difference between cabin and sea level air is the low humidity present in cabin air. This was found to range between 12% and 21% in a 1994 ATA study (5,6). Others have recorded as little as 5% humidity (7). Fluid consumption before and during flight easily compensates for the small increase in evaporative fluid loss. Ozone and carbon dioxide are the principal contaminants of cabin air. Aircraft may cruise through ambient levels of ozone in excess of 1.0 ppmv. Elevated ozone concentrations may cause headaches; eye, nasal, and pharyngeal irritation; as well as impair dark adaptation and visual accommodation. However, catalytic converters in the air intake effectively mitigate this hazard. The FAA limits average concentrations to 0.1 ppmv above 27,000 ft, and peak concentrations to 0.25 ppmv above 32,000 ft (8). Volatile organic compounds and tobacco smoke are of little concern now that smoking is prohibited on all U.S. and most international flights (9). Charcoal filters are in place to remove volatile compounds from the cabin air. Cabin air is exchanged every 3 to 4 minutes (aircraft with recirculation systems typically use 50% outside fresh air, and 50% recirculated air to increase humidity, and thereby passenger comfort. Additional humidification may be added (10). In newer generation aircraft, high-efficiency particulate air (HEPA) filters screen out microorganisms and particles equal or greater than 0.3 μm with 99.99% efficiency. In contrast, offices and homes exchange room air only every 5 and 12 minutes, respectively (11), and often do not employ HEPA filters. Contemporary cabin air studies have proved that cabin air quality is normally well within accepted standards and does not compromise aircrew or passenger health (7,12,24,25).

Transmission of Infectious Disease

Aircrew infection may result from aerosols and droplets containing respiratory pathogens, contaminated food and water, or exposure to insect-borne diseases such as malaria. Although the risk is low, tuberculosis (TB) transmission during air travel has occurred. Some forms of TB are multidrug resistant tuberculosis (MDR-TB) or extensively drug resistant tuberculosis (XDR-TB) and therefore potential spread in public places such as aircraft is of great public as well as clinical concern (13). Fortunately, aircraft cabin air filtration systems do a good job of filtering out organisms such as influenza, measles, TB, and (severe acute respiratory syndrome) SARS that otherwise would have the potential to become airborne and disseminate in droplet nuclei (14,15). Influenza is more likely to be spread by droplet than by aerosol transmission, which means that it does not travel far (maximum distance about 5 ft) from the source. However, the virus may also be spread by touching recently contaminated surfaces, and by ingesting or having mucous membrane contact with contaminated water or food. For airline travelers, personal protection may be achieved through hand washing, alcohol-based hand sanitizers (which work for influenza, but not for norovirus), avoidance of utensil or food passing, use of respiratory etiquette (e.g., covering mouth to sneeze or cough), and social distancing (3–5 ft). Masks may be an option (a surgical mask on the source to prevent spread, and N95 mask on those potentially exposed to prevent inhalation). Airlines carry surgical masks but generally do not carry N95 masks. The surgical masks are in a first aid kit and in a separate medical kit.

Acute and even incapacitating gastrointestinal illness occurs surprisingly frequently; being reported in up to 33% of international airline pilots at some point in their careers (16). Preventive practices include requiring aircrew to eat different meals at different times, implementing a food handler program with medical surveillance and sanitation training for kitchen staff, using an approved catering source with periodic (including no-notice) inspections, culturing equipment, surfaces, and finger swabs, ensuring proper holding temperatures, ensuring a safe, potable water supply, and ensuring proper waste removal (personnel engaged in this activity are not to include food handlers).

Finally, mosquito-borne diseases such as malaria may be transmitted to aircrew during layovers in areas infested with infected mosquitoes, or, rarely, by extended waiting in the aircraft while in such areas (17). The risk of infection is contingent upon the presence of endemic malaria in the area, duration of night time exposure, aircraft disinsection, and chemoprophylaxis (18). Aircraft disinsection has been an international practice since the 1920s. Many nations including the United States have discontinued the practice because of reports of insecticide-related illness among cabin crew and passengers, but aircraft disinsection is still sanctioned by international law. Residual application of pyrethroids is probably the most efficacious method (19). AGARD has published a *Guide on Aircraft Disinsection for Military and Civilian Air Carriers* (26).

Hazardous Cargo

Hazardous cargoes may pose potential threats to humans. They may be ignitable, corrosive, reactive, toxic, or radioactive (20). Two 1993 reports by Voge and Tolan evaluated the data in the USAF and Naval Safety Centers' hazardous cargo incident databases (21,22). Despite regulations prohibiting passenger transport on flights carrying hazardous cargo, infractions did occur. The most common cause was due to improper declaration of the hazardous cargo. Spills and fumes were the most common problems. Physiologic responses ranged from nausea and lightheadedness to loss of consciousness and involved aircrew, passengers, or both. Improperly packaged oxygen-generating canisters aboard ValuJet Flight 592 caused a cockpit fire that resulted in the aircraft crashing into the Everglades, the loss of all aboard (110 lives), and the bankruptcy of the airline (23). When transporting hazardous cargo, thorough planning and declaration, proper storage and well-defined handling procedures, current and comprehensive crew training, provision of protective equipment, implementing emergency procedures as necessary, and verification of proper transfer and full debriefing of errors, incidents, and actual mishaps are essential (see Chapter 9).

Personal and Interpersonal Factors

Aging

There is little doubt that cognitive and physical skills deteriorate with age. On the other hand, it is almost equally clear that piloting expertise increases as well. Consequently, determining a cutoff age for retirement that optimizes flight safety is far from a trivial task. The FAA instituted an age-60 mandatory airline transport pilot retirement age in 1959 (the "Age-60 Rule"), and in subsequent years, this was studied by several scientific committees (27) and sustained in multiple court challenges (28). Since 1978, ICAO standards have permitted first officers to fly until their 65th birthday, and in 2006, this was changed to allow pilots to serve as pilot-in-command up to age 65, provided that the other pilot is younger than age 60. The FAA Administrator subsequently commissioned an Aviation Rulemaking Committee (ARC) to study this matter, and a proposal to change the FAA standard. This has passed the senate brought forth by Senator Oberstar on 12-10-2007 and now awaits the President's signature. Additional longitudinal studies of air carrier and commercial pilots flying larger more complex aircraft are needed (29).

Fatigue

Aircrew fatigue may stem from circadian dysrhythmia, from sleep debt present before flight (induced by the use of coffee or alcohol, psychological stress, indigestion, or clinical sleep disorders), or from several days of trying to sleep at unaccustomed hours in different hotel beds or bases with various environmental stressors such as light, noise, or mosquitoes. Fatigue is common in flights that extend into the 2.00 to 5.00 AM circadian nadir, or that last over 10 hours. Fatigue may occur even on short-haul flights in familiar surroundings when there is a significant sleep debt. Fatigue and countermeasures are further discussed elsewhere in this volume (see Chapter 23).

Psychosocial Stress/Poor Communication

Inadequate coordination and communication between aircrew has been identified as a source of errors and mishaps since the 1980s. This may be manifest as reticence by first officers, navigators, or cabin crew to question captain/pilot authority due to gender, age, and cultural differences. Communication between military flight leads and other formation members, or between aviators and air traffic controllers, are subject to similar difficulties. Several generations of cockpit or crew resource management (CRM) initiatives have been implemented in both civilian and military arenas with varying degrees of success (30,31). Tailoring training to assure relevance to specific aircraft types (i.e., fighters versus helicopters) and operational-cultural environments has been recommended (32). Relationships with family at home, flight deck and cabin crew during layovers, management, and occasionally even passengers during flight (the most dramatic examples being "air rage" and hostage-taking incidents) are other sources of interpersonal stress.

Menses and Pregnancy

Menses and pregnancy are two physiologic processes unique to female aircrew. In theory, both could compromise flight performance and possibly safety, both of the flight/mission and of the female crewmember and her fetus. There are special concerns with respect to the effects of the high-G environment and long duration, and/or high-altitude flights, which increase exposure to cosmic ionizing radiation. Circadian dysrhythmia is known to adversely affect menstrual function in cabin crew (33). However, a USAF centrifuge study on female subjects showed no association between the phase of the menstrual cycle and performance during simulated air combat maneuver training up to $+7G_z$ (34).

For pregnant aircrew members, removal from flight duties at or shortly after conception would be most prudent, in order to reduce exposure to radiation and other potential hazards. However, individual responses to pregnancy (e.g., nausea, and vomiting in the first trimester) and individual acceptance of risk (e.g., cosmic radiation exposure) are variable. Many airlines therefore permit female pilots and cabin crew to continue flying until 20 to 27 weeks (coinciding with growth of the pregnant uterus over the protective upper pelvic rim and with onset of mobility restrictions on the part of the crewmember) or later.

Tobacco Use

There is incontrovertible evidence that smoking and the use of smokeless tobacco products are deleterious to health (35). Also, each cigarette contributes a "dose" of carbon monoxide equivalent to as much as an additional 5,000 ft of altitude. As early as 1989, the prevalence of smoking was only 24% among U.S. Army aircrew, in contrast to 39% among brigade support personnel. Prevalence of smoking among U.S. males at the time was 31% (36). A study of U.S. fighter aircrew in 2000 revealed that none of the 78 survey respondents smoked (37). Unfortunately, in some regions of the globe such as Eastern Europe, aviators have a much higher prevalence of smoking (1). Nicotine-induced withdrawal following smoking cessation is a potential aviation safety concern. Although psychoactive medication such as buproprion is contraindicated because of potential side effects, the use of nicotine replacement therapy is permissible (38). Grossman has reviewed treatment options for aviators who smoke (39). Varenicline for smoking cessation was approved by the U.S. Food and Drug Administration (FDA) in May of 2006, but has not been approved by the FAA at the time of writing. In the United States, smoking has been banned since 1989 in the passenger cabin, (initially for flights <6 hours in duration), and since 2000 smoking has been banned in the cockpit (40). ICAO, at its 19th assembly, in 1992, adopted resolution A29-15, which restricts smoking on international passenger flights (41).

Alcohol Use

More than 80% of American adults consume alcohol, with per capita consumption of approximately 25 gal/yr (42). Approximately 8% of full-time American workers use illicit drugs (43), and this may be an underestimation (44). The effects of alcohol and drugs on the performance of aircrew has been the subject of many research papers over the last 40 years (45), and violations frequently lead to public scrutiny (46). The number of serious errors committed by pilots rises rapidly when blood alcohol concentrations exceed 0.04%, and some studies have reported performance decrements at levels as low as 0.025% (47,48). Even when the blood alcohol concentration has returned to zero, performance and safety may be impaired for up to 15 hours after alcohol ingestion. This may be due to the effect of hangovers (49), fatigue due to reduced-rapid eye movement (REM) sleep (50). An increased incidence of sleep apnea and hypoxemic episodes also follows alcohol ingestion before bedtime (51) (see also Chapter 9).

Illicit Drugs

A comparison of postmortem specimens from fatal civil aviation accidents between 1994 and 1999 with those occurring between 1989 and 1993 revealed a 25% increase in the number of cases where illicit drugs such as cocaine, amphetamine, marijuana, and barbiturates were found (52). However, the prevalence of such drug use among Class 1 air transport pilots declined from 2.8% to 0.8% during the same period, probably as a result of the drug testing program of the Department of Transportation (DOT). Although controversy exists regarding the short- and long-term effects of many drugs, as well as the social implications of their use, they are unacceptable in any cockpit. Most illicit drugs cause side effects (drowsiness, euphoria, impaired mentation, hallucinations, and flashbacks) that categorically threaten flight safety and performance. The aviation practitioner should be familiar with common illicit drugs and discourage their use among the aviators under his or her care. Health behaviors of military servicemen, including use of tobacco, alcohol, and illicit drugs have been periodically surveyed since 1980, with the latest survey having been completed in 2005 (53–55).

Self-Medication

Potential side effects of prescription and over-the-counter (OTC) medication, including some herbal supplements such as melatonin, valerian, and St. John's Wort, include drowsiness, hypotension, decreased visual acuity, nausea, dizziness, and subtle impairment of higher neurologic function, only evident with sophisticated testing such as CogScreen Aeromedical Edition (56). With the exception of limited authorized OTC medications, both civilian and military aerospace medical regulations require aircrew to turn to their flight surgeons for treatment or advice on medication use. Following adequate medical review, aviators may be issued waivers to fly, with the proviso that there be reasonably close tracking by the flight surgeon. Despite these safeguards, postmortem studies of mishap pilots have turned up blood levels of various drugs incompatible with safe flight, including sedating antihistamines, antidepressants, and antiseizure medication (52,57).

Sedentary Lifestyle

Most pilots have a sedentary lifestyle that may lead to weight gain, the development of insulin resistance, hyperlipidemia, hypertension, and eventually diabetes and cardiovascular complications including coronary heart disease (CHD) and cerebrovascular disease. CHD is a leading cause of denial or loss of licensure in both civilian and military aviators (58). Although flying consists primarily of light physical activity, physical fitness is a readiness issue for military aircrew. Military pilots are therefore encouraged to exercise regularly, and the provision of fitness programs and facilities on base and the use of periodic physical assessments ensure compliance (59–61). Few airlines and commercial flight organizations have adopted health promotion or fitness programs for aircrew, and in general aviation, there is no regulation of lifestyle at all. As the prevalence of obesity and its complications among the general public continues to grow, an increasing number of aircrew will develop and be limited by health problems induced by sedentary lifestyle (62–64).

Nutrition

Both military and civil aviation are rapid paced and geographically diverse, resulting in aircrew often not eating at regular times or locations. Obtaining freshly prepared meals containing a variety of healthy foods can also be a challenge. These factors can lead to dietary behaviors that may negatively impact health, flight safety, and/or performance, including risking hypoglycemia and dehydration by skipping meals, eating fat- and salt-laden snacks and meals, and overindulging in caffeine- and sugar-rich beverages. Consumption of gas-forming food and drink, such as legumes and carbonated beverages, before and during flight, has traditionally been discouraged. The intent is to avoid discomfort from expanding abdominal gas at altitude, which may be a problem particularly for military aviators. Aircrew should follow dietary guidelines with the goal of a healthy diet (65). The energy needs of piloting aircraft are variable. The maximum energy expenditure in a 70-kg pilot while flying is approximately 150 kcal/hr, twice the 75 kcal/hr energy expenditure of sitting quietly, but less than half the 380 kcal/hr of walking 4.0 mph (66–69).

Acute and Chronic Illness

In the selected and regularly screened aircrew population, the incidence of serious incapacitating illness is rare, as described later in this chapter. Flight safety and performance are more likely to be affected by acute illnesses such as neck and lower back sprains, and ankle injuries, respiratory tract infections, and gastroenteritis. Ear and sinus barotrauma may result from flying with inflamed respiratory mucosa, while dehydration-related reduced $+G_z$ tolerance and impaired higher cognitive function can result from gastroenteritis. Prudent flight surgeons will both make these hazards known to younger, inexperienced aircrew and work toward primary prevention through staying up to date on standard immunizations, hygienic food preparation, assuring aircrew keep well rested and hydrated, and helping them manage seasonal allergies safely and effectively.

Certain recurrent subacute or chronic illnesses such as migraine headaches are a challenge to diagnose, treat, and therefore address aeromedically (see Chapter 16). Given its 5% to 15% prevalence in the population (70), its subjective nature, and the threat of grounding if diagnosed, it has been assumed that migraine headaches are underreported by aircrew. Until better epidemiologic data and more objective diagnostic techniques are developed, flight surgeons can best approach these issues through relevant aeromedical briefings and by establishing good rapport with crewmembers.

EPIDEMIOLOGY AND PREVENTION OF DISEASE AND DISABILITY

Military Air Crew

Epidemiologic studies on civilian and military aircrew have been conducted to determine long-term effects of physiological stressors of flight, and by application of their findings retrospectively to better define selection criteria.

Graybiel et al. began a study of 1,056 male students and instructor pilots in 1940, which has come to be known as the *U.S. Navy's* 1,000 Aviators *Study* (71). Surviving pilots who could be contacted have been medically reassessed periodically since then. In 1978, McIntyre reported that compared with unselected American males, the "1,000 Aviators" were half as likely to die of cardiovascular disease (72). York subsequently observed a significant difference within the cohort between those who were alive in 1981 (73) and those who had died between 1970 and 1980. The 114 survivors were more likely to exercise regularly, to abstain from cigarette smoking, and to drink alcoholic beverages moderately. He concluded that healthy lifestyle might alter cardiovascular risk, preventing premature death. The "WestPoint Study" prospectively assessed cardiovascular disease and mortality in a cohort of 474 male military officers who entered the U.S. Military Academy in 1952 (74). In addition to biennial medical examinations, there were two more extensive assessments conducted at United States Air Force School of Aerospace Medicine (USAFSAM) and Armstrong Laboratory in 1975 to 1979 and 1988 to 1992. Using risk factors (serum cholesterol, estimated high-density lipoprotein (HDL) cholesterol, systolic blood pressure, and smoking status) measured before age 28, the investigators were able to predict which members of the study, had they been pilots, would have been grounded for coronary artery disease (CAD) before age 55. They concluded that selection of candidates from the lowest tertile of risk-related scores would yield a population of pilot trainees who would have a very low incidence rate of CAD up to age 55.

Grayson and Lyons retrospectively reviewed records of more than 200,000 USAF male air crew who worked at least 1 year between 1975 and 1989, comparing rates of cancer in this population with the SEER Surveillance, Epidemiology, and End Results, a program of the U.S. Cancer Registry standard population data. Air Force pilots were found to have increased standardized incidence rates (SIRs) for skin and bladder cancer, but a decreased rate for Hodgkin's disease (75).

McCrary and VanSyoc noted that the USAF has improved its ability to retain experienced aviators, with permanent flying disqualifications dropping from 4.1% per year in 1984 to 0.18% per year in 1995 to 1999 (76).

Air Crew of Commercial Airlines

The ICAO, the FAA, and the European Joint Aviation Administration (JAA), in addition to government bodies in other countries, have set standards for the certification of pilots, with airline transport pilots being subject to the highest level of scrutiny.

Most epidemiologic studies conducted on commercial airline pilot populations before 1990, concerned medical disqualification and/or in-flight incapacitation. More recent studies have examined morbidity and mortality more generally, with particular attention to cancer.

Airline Pilot Disability and Mortality

Preston reported 73 disqualifications among 1,000 British airline pilots who had flown between 1954 and 1965, of them 49% for psychiatric and 10% for cardiovascular reasons (77). Twenty-two of 27 pilots who died (81%) did so as a result of a noncommercial aircraft accident. LaVehrne found that among 1,250 Air France pilots, there were 64 permanent groundings, 34% for cardiovascular and 17% for psychiatric reasons (78), while Kidera observed that of 123 medical groundings of United Airlines pilots between 1938 and 1966, 42% were for cardiovascular and 14% for psychiatric reasons (79). In another U.S. airline pilot population (Northwest Airlines), Orford found that cardiac disease accounted for 51%, psychiatric diagnoses for 13%, and neurologic problems for 12% of 103 medical retirements (80). Holt updated the study in 1985, again finding that cardiovascular disease was responsible for 50% of the medical losses in the years since the first study (81).

Band et al. conducted mortality and cancer incidence studies of pilots in two Canadian airlines. Of 913 Canadian airline pilots employed from 1950 through 1988, he found that 71 had died, 23 (32%) in aircraft accidents, 18 (25%) from cardiovascular conditions, 16 (23%) from cancer, and 14 (20%) from other causes (82). For all causes, the standardized mortality rate (SMR) was lower than expected (0.80) consistent with the "healthy worker" effect (healthy workers have lower overall death rates than the general population due to exclusion of the severely ill and disabled). However, SMRs were significantly raised for aircraft accidents (21.29), rectal cancer (4.35), and brain cancer (4.17). There were 57 incident cancer cases ascertained from provincial cancer registries with significantly elevated SMRs being noted for Hodgkin's disease (4.54), primary brain cancer (3.45), and nonmelanoma skin cancer (1.59).

In a second study, of 2,740 Air Canada pilots employed for at least 1 year between 1980 and 1992, Band again observed a significant reduction in mortality from all causes (SMR 0.63) and an elevated SMR for aircraft accidents (26.57). Among cancers, SMRs for acute myeloid leukemia (4.72) and prostate cancer (1.87) were significantly increased, although the SMR for all cancers (0.61) was significantly decreased. SMRs for malignant melanoma were increased in both studies, but not to the level of statistical significance (83).

In another study, Band found that long-term disability (LTD) rates among Air Canada pilots increased with age, rising from 1.86/1,000 pilots/yr at age 20 to 29, to 9.22/1,000/yr in those aged between 50 and 59 (84). Injuries were most significant among the younger pilots (66% of all causes of LTD under age 30); mental disorders including alcoholism were the most prevalent noninjury conditions among pilots aged 30 to 49 (25.4% of noninjury); while ischemic heart disease was significant in the oldest age-group (27.9% of all noninjury causes between age 50 and 59). Band pointed out that more attention to physical conditioning and other lifestyle modification measures could have prevented many of the injuries and circulatory disorders. He urged pilot associations and airline companies to work together to ensure that preventive programs are implemented.

Irvine and Davies used proportional mortality ratio (PMR) methodology to study mortality and life expectancy in British Airways flight deck crew between 1966 and 1989. Cause of death was ascertained in 411 of 446 cases, and "the predictable excess of aircraft accidents was removed." Significantly elevated PMRs were observed for malignant melanoma (6.69), cirrhosis (2.88), colon cancer (2.30), and brain/central nervous system (CNS) cancer (2.68) (85). These authors subsequently extended their study to all British Airways pilots and flight engineers employed for at least a year between 1939 and 1992 (86). Standardized mortality ratios for cirrhosis, brain/CNS cancer, and colon cancer were found to be no longer elevated to a level of statistical significance. The SMR for melanoma was significantly raised for pilots, but not for flight engineers. The reason for this difference was not determined. Life expectancy for both groups exceeded that for the general population of England and Wales, even when social class differences were taken into account. Besco et al. similarly found that retired American Airlines pilots had a residual life expectancy after age 60 of greater than 5 years longer than the U.S. population of 60-year-old white males (87).

All of the preceding studies concerned male pilots. The first airline pilot in the United States was not hired until 1973 (by Frontier Airlines). Nicholas published the first epidemiologic study concerning female pilots in 2002 (88), with a follow-up study concerning an observed increase in breast cancer in this population in 2003 (89). Additional studies on disability and mortality among female pilots are needed.

Ballard et al. conducted a meta-analysis of six cohort studies concerning male pilots and female flight attendants reported between 1986 and 1998. For pilots, overall mortality rates were decreased for all causes, lung cancer, all leukemia, ischemic heart disease, and respiratory disease (90). Using a statistic he termed *combined socioeconomic status relative risk*, he determined that cancer mortality rates were elevated for melanoma (1.97) and brain cancer (1.45), whereas cancer incidence rates were elevated for prostate cancer (1.65) and brain cancer (1.74).

A proportionate mortality study using mortality data from 24 U.S. states from 1984 and 1991 found that cancer of the kidney and renal pelvis was the only cause of death to be significantly increased among male pilots (PMR 1.96) (91). The authors noted that associations between kidney cancer and aviation fuels have been reported in other occupational health studies. However, this finding contrasted with the British Airways and Air Canada studies, both of which found significantly lower rates than expected for kidney and bladder cancer among pilots (83,86). Finally, a large European study of 28,066 male and 262 female cockpit crewmembers found an increased mortality from malignant melanoma (SMR 1.78) and from aviation accidents, but a reduction in mortality from lung cancer (SMR 0.53) and cardiovascular disease (92).

In summary, contrary to popular belief, airline pilots have an overall lower mortality rate than the general population, and on average live as much as 5 years longer than the general population after age 60. Mortality from noncommercial aircraft accidents is significantly raised. The most common reasons for medical disability are injuries among pilots younger age 30, mental disorders including alcoholism among pilots between 30 and 49, and circulatory disorders among pilots older than 50. Many of these conditions would be preventable by lifestyle modification. With the possible exception of melanoma, no form of cancer is consistently elevated in the pilot populations studied, and overall, the cancer rate for pilots is lower than the general population.

In-Flight Incapacitation

Episodes of in-flight incapacitation are frequently experienced by airline pilots [27%–29% of International Federation of Airline Pilots' Associations (IFALPA) pilots surveyed in 1968 and 1998 reported having experienced at least one such occurrence] (16,93). The most frequent reason is gastrointestinal disturbances (uncontrolled diarrhea, nausea, vomiting, or severe indigestion). However, very few pilots report these events spontaneously and few, if any, commercial airline accidents have been attributed to pilot incapacitation or for medical causes (94). This contrasts with general aviation, where several accidents caused by in-flight incapacitation occur each year as a result of cardiovascular/cerebrovascular events, alcohol or drug use, carbon monoxide poisoning, or seizures (95). Human factors specific to aviation may also cause or contribute to in-flight incapacitation, including hypoxia, spatial disorientation, and improper G-protection maneuvers, as described elsewhere in this text (see Chapters 2, 4, and 6). Most cardiovascular deaths in pilots younger than 35 years are due to hypertrophic cardiomyopathy (based on the sports medicine literature), whereas in men older than 35 years, nearly all are due to CAD. Autopsy studies have shown the prevalence of significant CAD in pilots to be similar to that in the general population (96). In addition, although the mortality rate for cardiovascular disease among younger pilots is lower than the general population, cardiovascular mortality among older pilots approaches that found in the Framingham study (Table 11-2) (97). DeJohn has reviewed in-flight incapacitation studies conducted between 1968 and 2000 (98). Mitchell and Evans examined the use of the "1% rule" by governments to set limits for aircrew incapacitation, and concluded that it may be too restrictive. They recommended instead that the maximum acceptable sudden incapacitation limit should be set at 2% per year (99).

TABLE 11-2

Incidence of Coronary Heart Disease, Airline Pilots Association (ALPA) and Framingham Study of White Males (Age-Specific Incidences Per 1,000 persons)

Age-Group	*Framingham Study*	*ALPA*	*Framingham/ ALPA Ratio*
29–34	2.93	0.151	19.40
35–39	2.44	0.678	3.60
40–44	5.16	2.050	2.52
45–49	7.23	4.460	1.62
50–54	12.70	8.740	1.45
55–59	19.80	15.900	1.25

(Adapted from Kulak LL, Wick RL and Billings CE. Epidemiological study of in-flight airline pilot incapacitation. *Aerosp Med* 1971;42:670–672.)(100)

Cabin Attendants

The mortality and incidence rates for cancer among 1,577 female and 187 male cabin attendants were studied by Pukkala and Auvinen (73). He observed statistically significant increases in SIR for breast cancer (1.87) and bone cancer (15.10), with the breast cancer risk being most prominent 15 years after recruitment. Significant increases for leukemia (3.57) and melanoma (2.11) were also seen. Lynge similarly reported an increased risk for breast cancer among Danish cabin attendants (SIR 1.61), although because of small numbers it was not statistically significant (101). Wartenberg found an increased risk of breast cancer (SIR 2.0) among retired U.S. female cabin attendants (102). Linnersjo found an SIR of 1.01 for cancer overall, and 1.3 for breast cancer (a nonsignificant increase), among Swedish cabin crews, although both men and women had increased rates of melanoma and nonmelanoma skin cancers (103). Similarly, Haldorsen failed to find an increase in breast cancer incidence among Norwegian airline cabin attendants (SIR = 1.1), but he reported an increased incidence of melanoma and nonmelanoma skin cancers (104). Elevated SMRs for acquired immunodeficiency syndrome (AIDS) and aircraft accidents have been reported among male cabin crew (105).

A number of studies have examined the risk for spontaneous abortion and menstruation irregularities among female cabin attendants. Cone and Vaughan reported a 15% rate of spontaneous abortions among 9,392 flight attendants who were pregnant at any time between 1990 and 1991 (106). This is comparable to the 10% to 20% rate reported for the general U.S. population. Aspholm reported in a retrospective Finnish study of 1,751 pregnancies among female cabin crew aged between 24 and 39, with the onset of pregnancy between 1973 and 1994, a spontaneous abortion rate of 12.1% (107). Again, this rate is similar to that for all Finnish women. Both studies showed a slightly increased spontaneous abortion rate among those who worked during the first trimester of pregnancy, but pointed out that any employment during the first trimester may be a risk factor for spontaneous abortion. Pregnancy outcome among cabin attendants (and pilots) is similar to that of the general population (108).

The U.S. National Institute for Occupational Safety and Health (NIOSH) has published several papers to characterize radiation and other exposures in the aircraft cabin environment and to assess health effects among flight attendants and pilots as part of the "Flight Crew Research Program."

Passengers

Agredans has reported that accessibility to air travel correlates strongly with melanoma incidence, and attributes it to increased UV radiation exposure and sunburn among travelers to sunny leisure destinations (109). However, Rafnsson found no difference in the prevalence of risk factors for malignant melanoma between a random sample of the population and aircrew, and concludes that the increased incidence of malignant melanoma found in previous studies of pilots and cabin attendants cannot solely be explained by excessive sun exposure (110).

MEDICAL CERTIFICATION OF CIVILIAN AVIATION PERSONNEL IN THE UNITED STATES

The United States has long been recognized for its expertise in civil aeromedical certification, with more than 75 years of experience in this discipline and well over 5 million civil airman medical cases on file. This unique wealth of civil aeromedical experience coupled with well-defined aeromedical research programs provides a strong framework for current aeromedical certification practices.

The FAA is the sole Federal government regulatory agency charged with oversight of civilian aviation and the commercial use of space in the United States. It is charged with both promoting the development of the aerospace industry and creating regulations that affect its day-to-day operations, from aeromedical certification to launches of commercial space vehicles. These responsibilities drive policy development in the FAA. In addition, as one of the original states represented in the 1946 Chicago Convention, the United States adheres to the principles of the ICAO and periodically undergoes program review by that organization to gauge adherence to international aviation principles. Guidance on the technical application of those principles is set forth in a set of 18 annexes known as the *International Standards and Recommended Practices* (SARP); those for aeromedical certification are contained in Annex 1, Personnel Licensing (111) (see also Chapter 28).

HISTORICAL PERSPECTIVE

The FAA as such came into existence in 1966; however, the roots of the organization can be traced back to 1926. Similar to today's FAA, the organizations that preceded the agency had also been charged with the responsibility of overseeing aviation activities and regulating air commerce, including the development, implementation, and refinement of civilian aeromedical standards.

Concurrently with the development of the civilian aeromedical standards, the military services were developing and refining their own standards, a subject covered elsewhere in this textbook. As they did in many other countries, military standards in the United States influenced early civilian standards. However, as civilian aviation grew and developed, the differences between these two medical certification philosophies widened considerably. Owing to mission requirements, military standards remained fairly restrictive while civilian standards became more flexible to accommodate the rapid growth of air commerce and meet the expanding needs of the general aviation industry.

The early beginnings of Federal government regulation of aviation and air commerce can be traced to the Air Commerce Act of 1926. Herbert Hoover, then Secretary of Commerce, established the Aeronautics Branch to administer this new aeronautical responsibility. The Air Regulations Division and the Air Information Division were created within this branch, and aeronautical activities were grouped by function in the divisions. In addition to offices with responsibilities in inspection, engineering, licensing, and enforcement, the Medical Section was placed in the Air Regulations Division. Before 1926 an organized civil aeromedical system did not exist in the United States.

In November 1926, Louis Hopewell Bauer was appointed the first director of civil aviation medicine (112). Dr. Bauer was a former Army flight surgeon who brought a considerable background of training and experience in the relatively new field of aviation medicine (see also Chapter 1). Early in his tenure as director of the Medical Section, Dr. Bauer developed the first civil physical standards and examination frequencies for determining the medical fitness of pilots. In drawing up these standards, Dr. Bauer concluded that strict adherence to military standards was not required for civil aviation because the military requirements related not only to flying but also to carrying out other military duties. He also recognized that military standards were designed to establish a selection process that would assure the military service of a long and useful career for the aviator and that such considerations did not apply to civilian pilots.

Before his resignation on November 26, 1930, Dr. Bauer reached a number of milestones in the establishment of a medical regulatory system for civil aviation. He proposed a system of federally employed district flight surgeons in 1928, completed studies of the correlation of physical deficiencies with aircraft accident and training success, and established procedures for conducting practical flight tests for granting "waivers" of the medical standards.

Early Standards

The first civil physical standards became effective on December 31, 1926 (113). Dr. Bauer, with the assistance of other medical experts, identified disqualifying conditions that he concluded could cause sudden incapacitation or death while at the controls of aircraft, or could otherwise compromise a pilot's ability to operate an aircraft in a manner compatible with an acceptable level of safety. To this day, this approach to disqualifying conditions remains the basic tenet of aeromedical certification in the United States. Like the military standards that influenced their creation, civilian standards were empirical in origin. Moreover, they contained many of the same rigid characteristics of the military standards and they retained these characteristics for many years.

Compared to the current standards the original ones were simple (see Chapter 1). They included three levels of physical qualification, one for each class of pilot created by the new regulations:

- Private pilots
- Industrial pilots
- Transportation pilots

In March 1927, a fourth class of certificate, "limited commercial," was added to the standards for transportation pilots, and student pilots were included under the private pilot standards. Transport and limited commercial pilots were required to undergo a physical examination every 6 months, and industrial and private pilots required renewal of their medical certificates every 12 months.

Dr. Bauer originally intended that waivers of the standards would not be granted to new student pilot applicants but would be reserved for pilots who had operational experience. However, under congressional and industry pressure, and in part because of the erroneous issuance of medical certificates by the department's designated medical examiners to applicants who did not meet the standards, waivers were soon granted to both new and experienced pilots.

The decline of new student pilot certificates in 1930 was attributed to "unreasonable medical standards" rather than to the difficult economic times brought on by the Great Depression. Despite studies by Dr. Bauer and Dr. Harold J. Cooper showing poor progress in training and higher accident rates for pilots with physical defects, the 1930s saw changes made that relaxed visual acuity and other medical certification standards. Examples include the introduction of the concept of certifying pilots with static physical defects, such as loss of a limb, and the interval between physical examinations for noncommercial pilots being lengthened from 1 to 2 years.

The most significant change in the regulations was made in October 1959 when nine medical conditions with a high risk of sudden incapacitation or altered judgment that required denial for any class of airman medical certificate were identified. The nine were all identified as "mandatory disqualifying conditions" under the standards and included an established medical history or clinical diagnosis of the following:

1. Myocardial infarction
2. Angina pectoris
3. Epilepsy
4. A disturbance of consciousness without satisfactory medical explanation of the cause
5. Diabetes mellitus requiring insulin or other hypoglycemic drug for control
6. Psychosis
7. Drug addiction
8. Alcoholism
9. A character disorder severe enough to have repeatedly manifested itself by overt acts

Although the Federal Air Surgeon could not issue "waivers" to applicants with these conditions, the FAA Administrator could grant exemptions; however, exemption authority was delegated to the Federal Air Surgeon in 1971. Further changes in the regulations were made in 1972, when the standards for mental disorders were clarified by differentiating psychiatric from neurologic disorders. In addition, current psychiatric nomenclature of the time was adopted and standardized definitions for alcoholism, drug dependence, and personality disorders were introduced. In 1976, the vision standards were modified to permit the use of contact lenses *in lieu* of spectacles.

In May 1982, the medical standards were further amended. This change was prompted by three factors: a lawsuit against the agency regarding the granting of exemptions from the nine "mandatory denial" conditions; a Federal court decision finding that the alcoholism standard was in conflict with the Comprehensive Alcohol Abuse and Alcoholism Prevention, Treatment, and Rehabilitation Act of 1970; and FAA concern regarding misinterpretation of the cardiovascular standards by the National Transportation Safety Board (NTSB). The regulations were amended in four key areas to perform the following functions:

1. Permit the special issuance of medical certificates (i.e., "waiver") under the established standards rather than through an exemption process for those persons with a condition requiring mandatory disqualification.
2. Permit the issuance of a medical certificate under the regulations to an individual with alcoholism who could show evidence, satisfactory to the Federal Air Surgeon, of recovery including sustained total abstinence from alcohol for not less than the preceding 2 years.
3. Clearly indicate that significant CHD, even if treated, was disqualifying.
4. Preclude the granting of first-class medical certificates with functional limitations (e.g., limiting a pilot to specified duties such as those of a second pilot in command or flight engineer).

No further significant activity occurred until 1995, when an important amendment was made to the standards that provided authority for the denial of medical certification to a pilot based on the use of medication that would be considered contrary to aviation safety. The FAA issued this amendment after a decision by the United States Court of Appeals for the 7th Circuit (114). Shortly after issuance of the rule regarding medication, a comprehensive revision of the standards was made in early 1996. The revisions of the medical standards were necessary to reflect current medical knowledge, practice, and terminology. In addition, the standards were recodified to reflect current Federal government numbering. This was accomplished in mid-90s.

CURRENT MEDICAL STANDARDS

One significant difference between the United States and other countries pertains to those individuals requiring government-mandated aeromedical certification. The United States requires medical certification of pilots, flight engineers, flight navigators, air traffic control tower operators, and students training for these activities. Unlike many other countries, the United States does not require medical certification for flight attendants, flight dispatchers, mechanics, and a host of other aviation personnel.

The 1996 revisions to the medical standards represent the current medical certification standards of the Federal Aviation Regulations (FAR) in the United States. The medical standards are contained in Part 67 of Title 14 of the Code of Federal Regulations (14 CFR). Parts 61, 63, and 65 of 14 CFR provide the nonmedical certification requirements for pilots and flight instructors, flight crewmembers other than pilots, and aviation personnel other than flight crewmembers. Under these parts of the FAR, a pilot must hold a first-class medical certificate to perform duties requiring an airline transport pilot certificate, a second-class medical certificate must be held for performing duties requiring a commercial pilot certificate, and a third-class medical certificate must be held for performing duties that require a recreational or private pilot certificate. The combined student pilot and airman medical certificate may be issued for any class. Flight engineers and flight navigators are required to hold a second-class medical certificate, as are civilian air traffic control tower operators not employed by the FAA, the Department of Defense (DoD), or the U.S. Coast Guard. Persons who hold only glider or free balloon ratings are not required to meet any established set of medical standards; however, they must certify that they have no known medical defect that makes them unable to pilot a glider or free balloon. Under Section 23 of Part 61 (Part 61.23) of the FAR, a first-class medical certificate is valid for 6 months after the month of the date of the examination; a second-class medical certificate is valid for 12 months after the month of the date of the examination; and a third-class medical certificate is valid for 36 months after the month of the date of the examination for pilots younger than 40 years, and for 24 months for those aged 40 or older.

Currently there are notices for proposed rulemaking that will change the requirements for first-class medical certificates to 1 year for those younger than 40 years and maintain it at every 6 months for those older than 40 years. There is also proposed rulemaking to change third-class medical certificate requirements to every 5 years for those younger than 40 years and keep it at 24 months for those older than 40 years.

In 2004, a new airman regulation that had been discussed for at least 7 years came to fruition. This was the creation of a new class known as *sport pilot*. These airmen would be certificated to fly an aircraft whose weight was no more than 1,320 lb (600 kg) under visual flight rule restrictions with only one other passenger. The key thing here is that these airmen would only require a drivers' license instead of a medical certificate (FAR 2006, pgs 116–129). They would have to comply with the medical restrictions that applied to the driver's license in whatever state they resided, and the FAA legal counselors added the limitation, that if they previously had a medical certificate, they could not have had their most recent medical certificate on record denied, suspended, or revoked.

Part 67

The current FAA medical standards are divided into three categories applicable to first-, second-, and third-class medical certificates (115). With a few exceptions, the standards are identical from class to class; Table 11-3 contains a summary of these standards.

Under the changes instituted in the 1996 revision of Part 67 (116), the nine conditions that were previously specifically disqualifying were expanded to a total of 15. Today, the disqualifying conditions are an established medical history or a clinical diagnosis of the following:

1. Myocardial infarction
2. Angina pectoris
3. CHD that has required treatment or, if untreated, that has been symptomatic or clinically significant
4. Cardiac valve replacement
5. Permanent cardiac pacemaker implantation
6. Heart replacement
7. Epilepsy
8. Transient loss of control of nervous system function(s) without satisfactory medical explanation of the cause
9. A disturbance of consciousness without satisfactory medical explanation of the cause
10. A personality disorder severe enough to have repeatedly manifested itself by overt acts
11. Psychosis
12. Bipolar disorder
13. Substance dependence
14. Substance abuse within the preceding 2 years
15. Diabetes mellitus that requires insulin or any hypoglycemic drug for control

Distant vision standards for first- and second-class medical certificates were changed to delete the uncorrected vision standard. Corrected vision in each eye must, nevertheless, be 20/20. For third-class medical certification, the new standard mandated visual acuity of 20/40 or better in each eye, with or without correction. Near visual acuity standards were changed for first- and second-class medical

TABLE 11-3

Summary of Part 67 Medical Standards by Class of Medical Certificate

Medical Certificate Class/Aviation Activity *Medical standards*	*First Class (Airline Transport Pilot)*	*Second Class (Commercial Pilot/ Non-FAA ATC)*	*Third Class (Private Pilot)*
Distant vision	20/20 or better in each eye separately, with or without correction		20/40 or better in each eye separately, with or without correction
Near vision	20/40 or better in each eye separately (Snellen equivalent), with or without correction as measured at 16 in.		
Intermediate vision	20/40 or better in each eye separately (Snellen equivalent), with or without correction in those aged 50 or older, as measured at 32 in.		No requirement
Color vision	Ability to perceive those colors necessary for safe performance of airman duties		
Hearing	Demonstrate hearing of an average conversational voice in a quiet room using both ears at 6 ft with the back turned to the examiner or pass one of the audiometric tests below		
Audiology (must pass either test)	Audiometric speech discrimination test score of at least 70% in one ear Pure tone audiometric test, unaided, with thresholds no worse than: Frequency (Hz): 500 1,000 2,000 4,000 Better ear (dB): 35 30 30 40 Worse ear (dB): 35 50 50 60		
ENT	No ear disease or condition manifested by, or that may be reasonably expected to be manifested by, vertigo or a disturbance of speech or equilibrium		
Pulse	Not disqualifying *per se* Used to determine cardiovascular system status and responsiveness		
Electrocardiogram	At age 35 and annually after age 40	Not routinely required	
Blood pressure (BP)	No specific value stated in the standards; however, *AME Guide* recommends evaluation and possible treatment if BP is on average >155/95 mm Hg		
Psychiatric	No diagnoses of psychosis, bipolar disorder, or severe personality disorder		
Substance dependence or substance abuse	A diagnosis or medical history of substance dependence is disqualifying unless there is established clinical evidence, satisfactory to the Federal Air Surgeon, of recovery, including sustained total abstinence from the substance(s) for not less than the preceding 2 yr; *substance* includes alcohol and other drugs (i.e., PCP, sedatives and hypnotics, anxiolytics, marijuana, cocaine, opioids, amphetamines, hallucinogens, and other psychoactive drugs or chemicals)		
Disqualifying conditions	An applicant shall be disqualified if the applicant has a history of (a) diabetes mellitus requiring hypoglycemic medication, (b) angina pectoris, (c) coronary heart disease that has been treated or, if untreated, that has been symptomatic or clinically significant, (d) myocardial infarction, (e) cardiac valve replacement, (f) permanent cardiac pacemaker, (g) heart transplant, (h) psychosis, (i) bipolar disorder, (j) personality disorder that is severe enough to have manifested itself by overt acts, (k) substance dependence, (l) substance abuse, (m) epilepsy, (n) disturbance of consciousness without satisfactory explanation of cause, (o) transient loss of control of nervous system function without satisfactory explanation of cause		

ENT, ears, nose, throat; PCP, phencyclidine.
(Adapted from FAA. *Guide for aviation medical examiners*, 1999 edition.)

certificates to 20/40 or better, corrected or uncorrected, in each eye at 16 in.. A new intermediate vision requirement of 20/40 or better, corrected or uncorrected, in each eye at 32 in. (80 cm), was added for persons older than 50 years desiring first- or second-class medical certificates. For third-class medical certification, a near visual acuity standard of 20/40 or better, corrected or uncorrected, in each eye at 16 in. was added. Color vision standards for all classes of certificate were amended to read "ability to perceive those colors necessary for the safe performance of airman duties."

Hearing standards were modified, as was the standard referring to disorders of the ear. The latter was modified to specifically include vertigo and, in addition, other conditions that may affect equilibrium. The "whispered voice" test was deleted for all classes and replaced by a requirement that the applicant be able to satisfactorily accomplish at least one of the following three tests:

1. A conversational voice test of both ears at 6 ft, with the back turned to the examiner
2. Acceptable understanding of speech as determined by an audiometric speech discrimination test score of at least 70% obtained in one ear or in a sound field environment or
3. Acceptable results of pure tone audiometric testing of unaided hearing acuity according to the following table of acceptable thresholds:

Frequency (Hz)	*Better Ear (dB)*	*Poorer Ear (dB)*
500	35	35
1,000	30	50
2,000	30	50
3,000	40	60

Significant changes were made to the standards relating to neurologic disorders, mental disease, and use of drugs, including alcohol. The neurologic concept of transient loss of nervous system control was introduced to more effectively identify conditions that were not fully covered with the standard that applies to a disturbance of consciousness. The word *seizure* was substituted for "convulsive." The term *psychosis* was better defined to include any condition in which the individual had delusions, hallucinations, or grossly bizarre or disorganized behavior. The diagnosis of "bipolar disorder" was added to the standards to reflect terminology contained in the *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition* (DSM IV). The terms *substance dependence* and *substance abuse* were introduced to replace *alcoholism* and *drug dependence*. The new terminology was introduced to provide greater authority in dealing with pilots who use drugs and alcohol.

In 2006, two new sections to the airman regulations Part 61 were added. In Part 61.14 and 61.16 an employee participating in air carrier operations who is subject to drug or alcohol testing and refuses to take a drug test or to submit to alcohol testing or to furnish or release the results of this testing can be denied any application for certification for up to 1 year or have any certificate suspended or revoked (FAR 2006, pg 46–47).

The general medical standards remained unchanged to provide a vehicle for the agency to evaluate and assess a variety of conditions not specifically identified by organ system as disqualifying. The medical regulation that allows the FAA to grant a medical certificate to an individual who does not meet the standards is 67.401. The terminology for a *Special Issuance* was changed to *Authorization for Special Issuance of a Medical Certificate* or simply *Authorization*. The reader may see *Special Issuance, Authorization*, or *waiver* used interchangeably throughout the text but they all imply the same concept of granting a medical certificate to a person who does not meet a particular medical standard but is considered otherwise safe to perform aviation duties. In order to grant an Authorization, the Federal Air Surgeon may require the pilot to undergo a special medical flight test, a practical test, or medical evaluation for the purpose of making this determination. An Authorization is time limited and the individual must regularly renew the issuance by demonstrating that he or she can safely perform aviation duties. In addition, under Part 67, section 401 (67.401), the Federal Air Surgeon may issue a Statement of Demonstrated Ability (SODA) instead of an Authorization if the condition to be "waivered" is static, for example, loss of a limb or loss of an eye. The individual must be found fit to perform pilot duties without endangering public safety. Unlike the Authorization, a SODA is not time limited; it must be renewed only if the medical condition changes.

Certification Policies

To supplement the medical standards contained in Part 67 of the FAR, the Office of Aviation Medicine provides substantial guidance material created specifically for use by designated Aviation Medical Examiners (AME). *This Guide is no longer published as a written document but resides at the FAA website as the Guide for Aviation Medical Examiners* (117). This reference material is designed to assist in the interpretation and application of the regulations. This document contains general information outlining the legal responsibilities of designees and sets forth the conditions under which examinations are performed. The *Guide* describes examination techniques and criteria for qualification as well as instructions for completion of the application form. The *Guide* and recurrent training seminars provide physicians and the public substantial information regarding the many potentially disqualifying medical conditions that are not covered in the medical standards themselves. The URL address for the on line Guide is http://www.faa.gov/about/office_org/headquarters_offices/avs/offices/aam/ame/guide/.

Certification standards originate in the Federal government's regulatory process, which is often complicated and lengthy. Recommendations for amendment of the regulations and for changes in FAA policies regarding airman medical certification originate from a variety of sources, including individuals, other government agencies, or organizations that represent the interests of particular groups. To achieve even a minor change in the regulations, an extensive review process is involved. It is not unusual for several years to elapse between the internal establishment of a rules project and actual amendment of the regulations. In developing a regulatory project, an initial determination is made regarding the sufficiency of information to proceed with a proposal through an Advanced Notice of Proposed Rulemaking (ANPRM). The purpose of the ANPRM is to gather information and views on the suggested change. If sufficient data exist that indicate a rulemaking action is warranted, a Notice of Proposed Rulemaking (NPRM) is issued setting out the basis for the proposed rule as well as the proposal itself. After providing an opportunity for public comment and conducting any public hearings that may be required, the FAA reassesses the proposal and determines whether to proceed with an amendment of the regulations. If it is decided that a regulatory amendment is indicated, the amendment is issued by the Administrator with an effective date that allows aviation personnel to come into compliance with the requirements of the new rule.

THE PROCESS FOR AIRMAN MEDICAL CERTIFICATION

The underlying premise for issuing a medical certificate in the United States is that the holder of the certificate is not reasonably expected to become medically incapacitated during the period of validity of the said certificate. In order to ensure this premise, a two-step process of checks and balances has been established for issuance of an FAA medical certificate. The first step is taken by a designated AME who performs the physical examination on the applicant in accordance with established agency procedures and makes the decision whether to issue, defer, or deny the medical certificate. The second step is a review and final adjudication by the FAA of the certification decision made by the AME. This double review helps ensure that only those truly qualified to hold such certification do so. The FAA Administrator, through the Federal Air Surgeon, ultimately provides the final determination on any particular medical certification decision. Less than 0.1% of individuals who apply for a medical certificate are permanently denied certification for significant medical or administrative problems. The typical circumstance, and certainly most desirable, is for an applicant to leave the AME office with a valid medical certificate in hand because they meet the requirements for certification.

The Aviation Medical Examiner System

AMEs are physician designees of the FAA authorized to issue, defer, or deny medical certificates to any applicant whom they have personally examined and found to meet the established standards for the class of medical certificate requested. As of September, 2006 there were 4,574 civilian AMEs in the United States, 335 in foreign countries, plus 363 military flight surgeons designated to conduct second- and third-class FAA examinations on military installations (Aeromedical Education Division, *personal communication*, 2001).

Management of the national civilian AME system has been delegated to the nine FAA Regional Flight Surgeons (RFS). This responsibility includes initial designation, de-designation, and monitoring of aeromedical certification performance. Practicing, fully licensed physicians in good standing in their communities are designated on the basis of training and experience, adequacy of facilities for performing the prescribed examinations, and the need for examiners in the geographic area. Typically, preference for designation is given to those physicians who have extensive experience or training in aerospace medicine or who have a demonstrated familiarity with aviation operations. Before the initial designation, the physician is required to attend an FAA-sponsored training. Thereafter, as a condition of continued designation, an AME must receive FAA-provided continuing aeromedical education at least once every 3 years.

In addition to the civilian AME designated in the United States, the agency also has designated select foreign physicians to perform FAA examinations abroad as well as National Aeronautics and Space Administration (NASA) and military flight surgeons to conduct FAA examinations on their personnel as required. The authority to designate an AME in countries other than the United States and at United States military medical facilities has been delegated to the Manager of the Aerospace Medical Education Division at the Civil Aerospace Medical Institute (CAMI) in Oklahoma City. Designation of physicians in foreign countries is based principally on the need for an examiner in the physician's locality. Criteria for designation of international examiners are generally the same as those for AMEs in the United States. However, some flexibility is permitted with respect to seminar attendance, and the requirement to serve as an examiner for at least 3 years before designation as a senior AME, authorized to do first-class examinations.

A change in internal policies regarding the designation of military medical facilities and NASA clinics now requires that specifically identified military and NASA flight surgeons, rather than the facilities, be designated. This change in policy prevents military physicians other than the designated flight surgeon from conducting examinations and issuing FAA medical certificates.

The Federal Aviation Administration Review Process

Applications for airman medical certification, which contain the results of physical examinations conducted by an AME, are forwarded to the Aeromedical Certification Division (AMCD) at CAMI in Oklahoma City for the collection of data and processing of the applications. In calendar year 2005, CAMI received a total of 438,707 applications for medical certification. This total included 210,511 applications for first-class medical certificates, 87,912 for second-class certificates, and 129,459 for third-class medical certificates (118). A considerably smaller number of applications were received for review and certification decision in the nine regional offices. The nine RFS possess the same authority as the manager of the AMCD to issue or affirm medical certificates; in addition, they are also responsible for preparing cases for legal enforcement action against applicants who do not meet the medical standards and have not surrendered an issued certificate.

More than 1,400 applications for medical certification are received by the AMCD each working day and processed in electronic format. The electronic data is processed through several edit programs to ensure a complete record, and each application is screened for significant deviations from established medical criteria and compared with data on the applicant that are contained in agency files. The Aerospace Medical Certification Division is one of the first offices in the FAA to go totally electronic. By regulation, a U.S.

AME must electronically transmit the Form 8500-8 (flying examination). This is accomplished over the Internet. Once submitted the examination is in the Document, Imaging, and Workflow System (DIWS). This DIWS stores all the examinations and scanned documents that support an airman's medical certification. The cases are passed electronically from one person to another based on the pathology codes. The computer system initially performs an "autocoding" process on examinations issued by the AME and sends up to 90% of them to file. The remaining cases are considered as priority and processed by examiners. Examiners are trained by the AMCD but are not medical personnel; if they have a medically related question, they electronically forward the case to one of the physician medical review officers. The medical review officer will either request more information, issue, or deny the airman. Approximately 10% of the rejected cases require review and adjudication by AMCD medical officers.

When necessary, medical files are referred to consultant medical specialists located throughout the United States for review and recommendations regarding certification. Because many of the cases requiring specialist review involve cardiovascular disease, a group of cardiology consultants meets every other month in Oklahoma City to review cases and make recommendations for certification. Applicants who are denied certification by the Manager of the AMCD, or any of the nine RFS, may request reconsideration by the Federal Air Surgeon. When necessary, the support staff in the Medical Specialties Division of the Office of Aviation Medicine obtains additional information for the Federal Air Surgeon or obtains additional opinions from consultants.

Authorization for Special Issuance (Authorization) of a Medical Certificate

The authority to grant an Authorization, or waiver, is contained in Section 67.401 of the FAR. This authority is delegated not only to the Federal Air Surgeon, but also to the Manager of the AMCD and to each of the nine RFS. At the discretion of these FAA officials, a medical certificate may be issued to an applicant who does not meet the medical standards if the applicant shows to the satisfaction of agency officials that the duties authorized by the class of medical certificate requested can be performed without endangering aviation safety during the period in which the certificate would be valid. For purposes of determining whether an Authorization may be granted, the agency may authorize a special medical flight test, practical test, or medical evaluation. An applicant's operational experience as well as medical factors are taken into consideration. In determining whether the special issuance of a third-class medical certificate should be granted, consideration is given to the concept that in the exercise of the privileges of a private pilot certificate, the pilot should be free to accept reasonable risks that are not acceptable in the exercise of commercial or airline transport pilot privileges.

In issuing a medical certificate under Section 67.401, limitations may be placed on the duration of the certificate; follow-up special medical tests, examinations, or evaluations may be required; and operational limitations may be imposed (e.g., requiring the applicant to wear lenses, hearing aids, or a prosthetic device). Functional limitations (e.g., those that restrict pilot duties that may be performed) may be imposed on second- or third-class medical certificates, but not first-class certificates.

Consideration for an Authorization may be given in the case of any disqualifying medical condition; however, consideration does not guarantee issuance of the waiver. Should an Authorization be granted, risk to aviation safety is minimized through requirements that applicants with known significant disease undergo extensive clinical evaluations and, when certificated, provide periodic special evaluations to assess disease progression. By placing these requirements or limitations on certificates, the agency's intent is to establish a level of safety for those persons granted an Authorization that is equivalent to persons in the general pilot population who have no known disease.

Authorizations have been granted for all classes of medical certificates and for almost all conditions that are disqualifying under the provisions of Part 67. Although the range of conditions for which Authorizations may be granted is quite broad, criteria for proving recovery and stability are stringent. Flexibility in the granting of Authorizations increases as the duties and responsibilities of aviation personnel decrease. Therefore, there is greater flexibility in granting third-class certification as opposed to first- or second-class certification, especially when the duties do not involve the transport of passengers for compensation or hire.

In calendar year 2005 there were a total of 5,973 denials or 1.36% of total applications. Out of these denials, 5,527 airmen were denied for failure to provide, meaning they just refused to provide the FAA with the evaluations and testing to make a case for granting a waiver. The same year there were only 446 final denials or 0.10% of total applications that were denied after providing the FAA all the information (119).

Appeal Procedures

An important legal consideration not frequently understood by those outside the civilian aeromedical certification process is the fact that once an FAA medical certificate has been issued and affirmed, the agency cannot simply cancel or revoke it without due process. A medical certificate is considered affirmed 60 days after having been issued by an AME unless the FAA has requested additional information before that time or has otherwise notified the applicant they were not qualified. No equivalent of the military aeromedical grounding notice or so-called down chit exists in the FAA; legally this is not possible. Any action taken by the agency to deny, cancel, or revoke that certificate must be through the legal process. While the legal process plays out, an applicant who does not or may not meet Part 67 standards but is still in possession of a certificate is warned not to exercise the privileges of their airman and/or medical certificate under Section 53 of Part 61 (Part 61.53). This section specifically warns the individual that performance of aeronautical duties with a known medical deficiency, or while receiving treatments or medications that would cause them not to meet the standards, is a violation of the FAR.

Within 60 days of final denial of medical certification by the FAA, a pilot may petition the NTSB for a review of the denial. This review is limited to a determination of whether the agency has appropriately applied its standards, not whether the standards themselves are appropriate. On receipt of a petition for review, the NTSB assigns an Administrative Law Judge (ALJ) to hear the petition. A hearing is scheduled and conducted, usually at a location convenient to the pilot and his or her witnesses. The rules of evidence for these hearings are relaxed. The pilot has the right to be represented by legal counsel, and legal counsel always represents the FAA. Medical testimony is received from witnesses on behalf of the pilot and the agency.

On the basis of the information submitted at the hearing, as well as the testimony by experts, a determination is made by the ALJ as to whether the pilot qualifies under the medical standards. Either the pilot or the FAA may appeal an adverse decision directly to the five NTSB members. The Board members rarely hear oral arguments, relying primarily on the record established at the hearing and briefs submitted by each of the parties.

In those circumstances in which an NTSB proceeding results from a pilot's appeal of an FAA action taken within 60 days of the issuance of a medical certificate (either a denial of certification or a request for information followed by a denial), the burden of proving qualification is on the pilot. If the FAA action is taken more than 60 days after the issuance of a certificate, the burden of proof is on the agency. For this reason, timely receipt and review of applications for which AMEs have issued medical certificates are important objectives of the medical certification program. NTSB rules of practice in air safety proceedings are published in 49 CFR Part 821.

If the full Board finds for the agency, the pilot may appeal that decision to a United States Court of Appeals in the Circuit in which the pilot resides or in the District of Columbia. The FAA may also appeal an adverse NTSB decision to the Courts but only in those cases where the FAA challenges the applicant's eligibility for medical certification more than 60 days after the issuance of the medical certificate.

Certification Procedures in Select Medical Conditions

A comprehensive discussion of case management issues in aeromedical certification in the United States is beyond the scope of this textbook. However, select clinical conditions will be discussed to provide the reader with an overview of the civil aeromedical certification practices in the United States. From a global perspective, it is important to emphasize that there are as many ways to approach aeromedical certification cases, as there are governments and physicians. The procedures and philosophies discussed here are those applicable to the United States and its particular medical, regulatory, and legal climate. Civil certification procedures discussed may not be appropriate in other countries or in other circumstances. Discussion of other organizations' certification philosophies and procedures are covered elsewhere in this textbook.

In the United States, FARs are written to provide the highest level of safety when they pertain to operations that involve airline transport and other passenger-carrying activities or to commercial operations such as cargo transport. Current regulations permit a greater burden of risk for third-class medical certificate holders.

The current coding system in AMCD utilizes pathology codes that are somewhat similar to the International Coding System but do not use the International Classification of Diseases—Ninth edition (ICD-9) system. The ICD-9 coding system is to be added to the current coding system in the very near future. The current coding system has approximately 1,000 codes, some of which are administrative. Some of the medical codes include several related medical conditions under one code. See Table 11-4 for the top ten common codes from 2005.

Color Vision In the most recent version of Part 67, the requirements for granting medical certification to applicants with color vision deficiencies were better standardized. An individual would be considered to have passed the color vision requirements if he or she passes the American Optical Company Pseudoisochromatic plates, 1965 edition; Dvorine, 2nd edition; Ishihara, 14-, 24-, or 38-plate editions; or the Richmond, 1983 edition, 15-plates. However, other acceptable substitutes are outlined in the *Guide for Aviation Medical Examiners* (115). If the applicant fails any or all of these tests, the following restriction must be placed on their medical certificate: "Not valid for night flying or by color signal control."

To have this restriction removed the individual must request and pass a Signal Light Test (SLT), which is given by an FAA Flight Inspector at an airfield convenient to the

TABLE 11-4

Top Ten Most Common Pathology Codes

Rank	*Count*	*Description*
1	40,024	Hypertension with medication
2	25,291	Allergic conditions
3	19,458	Alcohol
4	14,930	Hernia
5	14,752	Kidney stone
6	13,893	Wears contact lenses
7	12,062	Driving while intoxicated
8	11,663	Gastroesophageal reflux
9	9,620	Hay fever
10	9,513	Medical appeals (special issuance)

Document, Imaging, and Workflow System. Oklahoma City, OK: Northrop Grumann, 2006.

applicant or the nearest FAA Flight Service District Office. The SLT demonstrates the applicant's ability to visualize aviation red, green, and white, which are deemed in Part 67 as the colors necessary for safe performance of airman duties. If the individuals pass the SLT, the FAA provides them an evidentiary letter as proof that they meet the standard. The evidentiary letter has taken the place of the previous SODA because it was determined that when an airman successfully passes the SLT, he or she meets the FAA standards.

Refractive Surgery Another controversial issue in the United States has been the granting of medical certification to airmen who have surgical correction of refractive errors. In the past, the FAA had been asked to certify a significant number of pilots and controllers with radial keratotomy (RK); however, currently the two most common procedures encountered in aeromedical certification in the United States are photorefractive keratectomy (PRK) and laser *in situ* keratomileusis (LASIK). These procedures may have side effects, such as corneal scarring or opacities, worsening or variability of visual acuity, problems with glare, and haziness of vision, which may be incompatible with aviation duties. Postoperatively the individual is required to meet the visual standards for the class of medical certificate they require even if it means that he or she must continue wearing glasses to pilot aircraft (120). Once recovery has progressed to the point that the treating physician confirms stable visual acuity and no significant sequelae, the individual must provide the FAA with a current eye evaluation to be granted an appropriate class of medical certificate. In calendar year 2006, there were 1,210 first-class, 1,404 second-class, and 3,146 third-class applicants certified with some type of refractive surgery procedures. AMCD listed the following numbers for PRK: 258 first-class, 273 second-class, and 697 third-class. During the same time period for LASIK there were 1,750 first-, 1,883 second-, and 4,570 third-class airmen certified (119).

Since the last edition of this book, the FAA is now permitting the use of multifocal contact lenses and intraocular lenses. The ophthalmologic specialists who advise the FAA felt that the science of these devices had progressed such that the vision would not be distorted when a pilot wears such lenses. The FAA is also permitting the use of accommodating lenses. These are lenses that actually substitute for the real lens in that they are attached to the ciliary body and adjust much like the real lens.

The policy for these multifocal lenses requires the airman to have a 3-month postsurgical grounding or observation period and for the extraocular multifocal lens a 1-month period before being considered for medical certification. They cannot have any complications adverse to flying such as glare, flares, or variable visual acuity. The airman must also meet the visual acuity standards for the medical class requested. This policy did not change the stipulation that airmen may not use monovision contact lenses, in other words a contact lens that corrects for near vision in one eye, and one that corrects for distant vision in the other.

Cancer The medical certification of various malignancies depends on the particular type of tumor or condition. The overriding concern in the medical certification of individuals diagnosed with some type of malignancy is the extent of metastatic spread. This is of particular concern if the malignancy could spread to the brain and produce seizures or cognitive impairment, or to some other organ system with the potential risk for sudden incapacitation. In addition, there is significant concern with the effect chemotherapeutic agents or radiologic treatments may have on the individual's ability to perform aviation activities. In civil aviation medical certification, this concern applies for the duration that the medical certificate would be in effect, that is, 6, 12, 24, or 36 months. If during this period, the individual could be expected to have significant negative impacts from the malignancy or the treatment(s) then aeromedical certification will not be possible.

In general, an applicant with cancer is informed not to engage in aviation activities until a specific diagnosis is determined and metastatic survey accomplished. If the tumor is very likely to metastasize, the applicant will be denied a medical certificate. If the tumor has metastasized at the time of initial diagnosis, the applicant will not be granted medical certification, or if he or she have a medical certificate, action could be taken to revoke the certificate. If the applicant is receiving chemotherapy, the applicant will typically not be permitted a medical certificate until a year past the therapy, assuming the tumor remains in remission.

Applicants with a history of cancer will be considered for an Authorization but must provide a comprehensive medical evaluation including, in appropriate cases, a metastatic survey and results of computerized tomography (CT) scans and/or magnetic resonance imaging (MRI) studies. If granted the Authorization, the applicant is then required to submit periodic follow-up reports. If a malignancy can be completely excised, with no gross vestige of the tumor remaining and the individual is otherwise asymptomatic, the individual could be allowed to return to flying as soon as fully recovered. A time limitation may be placed on the medical certificate thereby requiring the individual to provide regular follow-up reports.

Applicants with leukemia, especially the acute type, are usually not granted medical certification. Applicants with Hodgkin's lymphoma are granted medical certification once the chemotherapy and radiation treatments have been completed. Generally, the airman is not considered until he or she has been in remission for 1 year after treatment; however, exceptions have been permitted. In non–Hodgkin's Lymphoma as in Hodgkin's the FAA waits until the airman has completed therapy and is in remission. In general, most current forms of treatment for both of these conditions are acceptable. The airman is expected to demonstrate that the disease is in remission with various tests.

The agency strives to assess each case individually avoiding a rigid "cookbook" approach. This provides applicants with cancer every reasonable opportunity to continue flying if it is safe to do so. To emphasize this point, the approach used in a case of melanoma will be discussed so that the reader may appreciate some of the considerations taken in reaching a certification decision. With melanoma it is well known that there is an increased likelihood of metastasis if the lesions are greater than a Breslow depth of 0.75 mm. In addition, melanoma lesions that have spread to local lymph nodes react differently than lesions that have spread to distant lymph nodes, distant organs, or the brain. Therefore, individuals with melanoma lesions less than 0.75 mm in Breslow depth, and with no metastases, can be issued an unrestricted medical certificate. If the melanoma lesion is Breslow depth 0.75 mm or greater, with spread only to local or regional lymph nodes, FAA policy permits applicants to receive aeromedical certification through the Special Issuance process. However, the lesions and nodes must have been excised or otherwise treated and the individual found to be free of metastasis; subsequently the individual must provide periodic MRI scans of the brain and follow-up reports by their treating physician. If the melanoma has spread to distant nodes or organs other than the brain, the individual is usually denied aeromedical certification for 3 years. He or she will be reconsidered for an Authorization after that time but must provide a comprehensive medical evaluation, and is then required to submit periodic follow-up reports including MRI scans of the brain. If the melanoma has spread to the brain, the airman is denied for 5 years, and then he or she can request an Authorization after that time if he or she is clinically doing well. If granted the waiver, the applicant will also require periodic brain MRI scans, metastatic surveys, and follow-up clinical reports (121). In cases of other malignancies, a similar rational approach based on current clinical guidelines and risk assessment is utilized to reach a certification decision.

Hypertension Hypertension is one of the most common medical conditions for which individuals receive authorizations for aeromedical certification in the United States. As of 2005 there were 8,889 first-class, 12,766 second-class, and 37,932 third-class airmen issued with this diagnosis. Authorizations for all classes of medical certificates were issued for this condition. Although not specifically stated as a standard, the FAA has established a recommendation that the average sitting blood pressure at the time of the physical examination not exceed 155/95 mm Hg. Persistent elevations above this value will require a clinical evaluation and consideration for therapeutic intervention, if clinically indicated. For those individuals whose condition is well controlled and stable, with or without medication, the FAA encourages AMEs to issue a medical certificate while the applicant is in their office. This avoids certification delays that may occur if these cases are processed by the Aeromedical Certification Division.

The applicant diagnosed with hypertension is required to provide a letter from their attending physician, which discusses risk factors for CAD, family history of hypertension or heart disease, medications (if any), and mention any end-organ damage secondary to the hypertension. The applicant may be required to perform a stress test if there are increased cardiac risk factors or symptoms. They are expected to provide reports of a lipid profile and fasting blood sugar, and on the initial medical certification for the condition, they are required to provide an electrocardiogram report.

As for treatment, the FAA accepts all medications currently in use for hypertension with the exception of five: α-methyldopa, guanadrel, guanabenz, guanethidine, and reserpine. It is a recommendation from the FAA that, should a pilot be taking a β-blocker for treatment of hypertension (or any medical condition where this class of drug is recommended) he or she refrains from participating in acrobatic flight.

Coronary Artery Disease As mentioned earlier in this chapter all the cardiac conditions associated with CAD and its many treatments are specifically disqualifying under the FAR. These specifically include angina pectoris; myocardial infarction; CAD that has required treatment such as percutaneous transluminal coronary angioplasty (PTCA), stents, atherectomy, rotablation, coronary artery bypass grafting (CABG); and permanent pacemaker implantation.

Once diagnosed with CAD or any of the above-mentioned conditions, the individuals must apply for aeromedical certification under the Special Issuance process. If granted medical certification, they will receive a written Authorization letter and an appropriate class medical certificate with a time limitation. They will be required to demonstrate to the FAA that they are safe to pilot an aircraft during the time period that the Authorization and medical certificate are in effect. If at any time during this period they become symptomatic, the Authorization will be cancelled. Table 11-5 provides some statistical data from the AMCD on airmen certified with the various CAD-related conditions.

The applicant is required to wait 6 months after any of these cardiac events before being reconsidered for aeromedical certification. This interval is considered an observation period to watch for recurrence or worsening of

TABLE 11-5

As of May 2006 Aeromedical Certification Statistical Data for Coronary Artery Disease (CAD) and Related Procedures by Class of Medical Certificate

	First Class	*Second Class*	*Third Class*
Myocardial infarction	440	418	2,938
Coronary artery with PTCA	370	286	1,682
CAD with stent	548	437	2,940
CABG	368	381	3,178

CABG, coronary artery bypass surgery; PTCA, percutaneous transluminal coronary angioplasaty.

Document, Imaging, and Workflow System. Oklahoma City, OK: Northrop Grumann, 2006.

the disease, or complications from the treatments. At the end of the 6 months, the applicant is required to provide all the medical or surgical records pertinent to the event, a current cardiovascular evaluation, a lipid panel, a fasting blood sugar, and a maximal effort stress test. In addition, first- and second-class medical certificate holders are required to provide a radionuclide stress test, as well as a 6-month postoperative cardiac catheterization, to determine patency established by any procedure performed. The anatomic results of the catheterization are compared to the functional results of the radionuclide stress tests. In addition, the previously mentioned panel of cardiologists at CAMI reviews all cases involving first- and second-class medical certificate holders. The Federal Air Surgeon chooses these cardiologists to make clinical and aviation safety risk assessment recommendations on individual cases before the issuance of an Authorization.

In subsequent medical recertification, as defined by the time limitation of the Authorization, the individual is required to provide follow-up information, which as a minimum includes a current status of their medical condition, lipid profile, and fasting sugar, and maximal Bruce protocol exercise stress test. Individuals with first-, second-, and third-class medical certificates are typically followed up in 12-month intervals. In general, if an applicant demonstrates ischemia on subsequent testing, even if he or she is asymptomatic, medical certification will not likely be granted.

Valvular Heart Disease Valvular heart disease is also specifically disqualifying and requires medical testing to demonstrate to the Federal Air Surgeon that the individual is safe to pilot an aircraft. In the case of aortic stenosis when the transvalvular gradient reaches 40 mm Hg, or the valve area becomes 1.0 cm^2 or less, the individual is not granted medical certification until the valve is replaced or the condition otherwise improves. The one exception to these criteria is untreated mitral stenosis, which is not permitted under most circumstances. With any of the valvular pathologies, complications such as persistent arrhythmias, heart failure, systemic emboli, or any other significant events would preclude medical certification.

Currently available bioprosthetic and mechanical valves are permitted for aeromedical certification, as well as the use of oral anticoagulation medications at sufficient therapeutic levels.

Individuals with mitral valve prolapse (MVP) may receive aeromedical certification if there have been no sustained arrhythmias, or related conditions, such as stroke, or any other significant symptoms. Most cases of MVP usually receive aeromedical certification even if taking certain medications to control symptoms.

If a valve has been repaired rather than replaced, such as with annuloplasty or commissurotomy, the applicant may gain medical certification after an observation period of 3 months, provided a favorable cardiovascular evaluation is received. However, if a valve is replaced, the individual must wait 6 months postoperatively before requesting consideration for medical certification. They will require all the medical records surrounding the condition and surgery, a current cardiovascular evaluation, lipid panel and blood sugar tests, current maximal Bruce protocol stress test, current two-dimensional (2-D) echocardiogram with color Doppler, and 24-hour Holter monitor. Table 11-6 provides FAA statistical data on applicants with valve replacements currently certified.

TABLE 11-6

As of May 2006 Federal Aviation Administration FAA Statistical Data on Valve Replacement Cases by Class of Medical Certificate

	First Class	*Second Class*	*Third Class*
Mechanical valve	36	34	170
Tissue valve	34	40	151

Document, Imaging, and Workflow System. Oklahoma City, OK: Northrop Grumann, 2006.

The use of warfarin for anticoagulation with mechanical valve replacements is permitted for aeromedical certification in the United States; the FAA currently prefers airmen to have International Normalized Ratios (INR) values between 2.5 and 3.5 to be considered for certification.

Permanent Pacemakers With the increased reliability and decrease in size of permanent pacemakers, the FAA has been granting medical certification to applicants for all classes of medical certificates. The individual has a mandatory 2-month period of observation following placement of the pacemaker, replacement of a generator pack or pacemaker lead wire. Before consideration for an Authorization can be given, the individual must provide all medical records concerning the condition that led to the requirement for pacing and all surgical records related to the placement of the pacemaker including the make, model, and serial numbers of the pacemaker generator and lead wires. One of the cardiology consultants of the FAA monitors the malfunction alerts; any problems with a generator or lead wire will cause the applicant's Authorization to be withdrawn. Also the individual is required to provide all the pacemaker evaluations for the 2 months preceding the request for certification; a maximal Bruce Protocol Stress Test; current cardiovascular evaluation; lipid panel and blood sugar test; 2-D echocardiogram; and 24-hour Holter monitor. Pacemaker evaluations are then required every 6 months on all classes.

Significant emphasis is placed on whether the applicant is pacemaker dependent. The FAA defines pacemaker dependency as a rate less than 40 beats/min after the pacemaker has been turned off or set down to its lowest setting. The FAA has recently started to grant medical certification to pacemaker dependent third-class medical certificate holders, previously such individuals would not have been certified. Presently, however, first- and second-class medical certificate holders are not medically certified, if they are pacemaker dependent.

As of May 2006, the AMCD has issued medical Authorizations to 43 first-class, 60 second-class, and 333 third-class applicants with permanent pacemakers (122).

Heart Transplantation Heart transplantation is one of the specifically disqualifying conditions cited in Part 67. Currently no one has received an Authorization for this condition; however, at one time the FAA had a handful of airmen certified. When it was discovered that these individuals could develop a significant vasculopathy in all of the vessels of the transplanted heart, their Authorizations were withdrawn. The vasculopathy is the leading cause of death in the first year and because of the surgical denervation of the transplanted heart it occurs silently. The incidence of disease is 10% to 50% at 1 year and 50% to 90% by 5 years. Histologically, it manifests itself as mononuclear cell proliferation of the intima, presence of lipid-laden macrophages in all areas of the vessel wall, hyperplasia of smooth muscle cells, and intimal proliferation (123).

Diabetes Mellitus The United States is now granting Special Issuance medical certification to applicants who are diabetic and taking an oral hypoglycemic agent. The use of β-blocking agents for some other condition in addition to an oral hypoglycemic agent is not permitted because of the masking of the body's reaction to hypoglycemia and the risk for sudden incapacitation. All oral hypoglycemic agents, to include multiple drug combinations, are acceptable to the FAA for treatment. Metformin, the thiazolidinediones, sitagliptin, and Acarbose are the only oral agents permitted with β-blockers, as they do not cause hypoglycemia.

To be considered, the individual must be stable for 60 days before requesting medical certification. The applicant must provide the FAA a report from their treating physician documenting presence or absence of ophthalmic, cardiovascular, cerebral, renal, or peripheral vascular sequelae of the disease. Hemoglobin A1C level within the last 30 days is also a requirement.

As of May 2006, there were 548 first-class, 1,108 second-class, and 4,137 third-class airmen who were granted medical certification with diabetes taking oral hypoglycemic and/or antihyperglycemic agents.

In 1995, the political climate was such that the then Federal Air Surgeon convened a panel of endocrinology specialists who looked at coming up with guidelines for granting medical certification to diabetic patients treated with insulin. A detailed medical certification process was proposed and initially only air traffic control specialists (ATCSs) were issued. When these individuals performed well without incidents, expansion of medical certification to only third-class airmen was granted. It was the Federal Air Surgeon at that time who felt that third-class airmen would be those who would be allowed to be waivered versus first- and second-class airmen. This was so because, when an authorization for special issuance (waiver) is granted, the third-class airman accepts more responsibility for his own safety versus first- or second-class airmen. As of May 2006, a total of 462 diabetic individuals on insulin were granted Authorizations.

To be considered, the applicant must have been stabilized on insulin therapy for at least 6 months. In addition, they must have had less than two episodes of symptomatic hypoglycemia in the preceding 5 years, and none of these episodes should have resulted in loss of consciousness, seizure, impaired cognitive functioning, or intervention by a third party. The applicant must provide a current report of examination from their treating physician, two recent measurements of hemoglobin A1C, and the first of which must be at least 90 days before the most recent level. The insulin type and dosage must be specified and reference to the presence or absence of cardiovascular, cerebrovascular, peripheral vascular, or neurologic problems made. The applicant must also provide an evaluation from an eye specialist documenting presence or absence of clinically significant eye disease. If the applicant is 40 years or older, he or she must undergo a maximal graded exercise test. There must be documentation that the individual is trained in the use of a recording glucometer and has an understanding of the actions to be taken in the case of hypoglycemia and has the ability to properly monitor and manage their diabetes (117). To gain or maintain certification, the applicant with diabetes on insulin is required to observe an elaborate monitoring program requiring the use of a recording glucometer and glucose supplementation.

Substance Dependence or Abuse Substance dependence in the FAA defines substance dependence as the condition in an individual whose use of a substance, other than tobacco or xanthine derivatives, is evidenced by increased tolerance, manifestation of withdrawal symptoms, impaired control of use or continued use despite damage to health or impairment of social, personal, or occupational functioning. The FAA defines a "substance" as alcohol, other sedatives and hypnotics, anxiolytics, opioids, central nervous system stimulants such as cocaine, amphetamines, and similarly acting arylcyclohexylamines, cannabis, inhalants, and other psychoactive drugs and chemicals.

In 1974, the Human Intervention Motivation Survey (HIMS) program was developed by the FAA's Office of Aviation Medicine in conjunction with the Airline Pilots Association (ALPA) to monitor recovering airline pilots being treated for substance abuse or dependence. HIMS relies heavily on the employer's Employee Assistance Program (EAP) and peers who confront the substance dependent pilot and encourage them to enter inpatient treatment programs. Once the pilot is detoxified, completes the inpatient program, obtains a sponsor, and attends regular aftercare and Alcoholics Anonymous/Narcotics Anonymous (AA/NA) meetings he or she can return to flying with an Authorization that requires very close monitoring. The monitoring requires regular attendance at aftercare programs, AA/NA meetings, and follow-up with a physician addictionologist. This is all monitored by an AME who receives extra training in observing for signs of relapse and sends periodic reports to the FAA's Aeromedical Certification Division in Oklahoma City. The period of follow-up typically runs for 2 years but could last up to 5 years for those pilots who relapse. This program has allowed thousands of pilots to get back to flying in as soon as 90 days after confronting and dealing effectively with their problem.

However, it is quite difficult to regain medical certification in the case of third- class certificate holders. Because of the lack of an established support system and monitoring that can be provided by an employer, the private pilot must demonstrate a period of complete and total abstinence of at least 2 years to be considered for an Authorization. Part of the requirement for continued medical certification in all classes of airmen is that they remain totally abstinent from the substance they abused.

As of May 2006, there were 992 first-class, 348 second-class, and 520 third-class airmen who had received Authorizations after being diagnosed alcohol dependent (122).

Medication Use in General The use of medications by aviation personnel has always been controversial. Some countries tend to be liberal in permitting use of medication whereas others are considerably more restrictive. Concerns arise not only with the medication use but also for the medical condition for which one either self-medicates, or for which medication is prescribed. In general, any individual who is receiving "continuous treatment with anticoagulants, antiviral agents, anxiolytics, barbiturates, chemotherapeutic agents, experimental agents, hypoglycemic, investigational, mood-ameliorating, motion sickness, narcotic, sedating antihistaminic, sedative, steroid drugs, or tranquilizers" must be deferred (FAA aeromedical) certification (117).

Use of the nonsedating antihistamine medications such as fexofenadine hydrochloride or loratidine is permitted provided the applicant does not have any side effects. The use of the nonabsorbed steroid nasal or pulmonary inhalers is allowed in allergic rhinitis and asthma. Once again, this assumes that the allergic rhinitis or asthma is not severe enough to warrant disqualification. In conditions where steroids are utilized, an equivalent dose of 20 mg or less of prednisone daily is allowed. The reasons for this are varied but primarily relate to increased side effects with higher doses, the increased incidence of hyperglycemia, and steroid-induced psychiatric changes (steroid psychosis). In addition, higher doses of steroids may indicate a worsening of symptoms, which would by themselves possibly preclude someone from exercising pilot privileges.

Nonsteroidal anti-inflammatory agents, and the newer cycloxygenase-2 (COX-2) inhibitors, are permitted in civil aviation in the United States. Once again, the condition being treated is an important factor. For example, an applicant with acute lumbosacral strain, or some significant arthritic process, should probably not fly during the acute, painful, and incapacitating stages of the condition.

With the exception of centrally acting antihypertensive agents, all classes of antihypertensive medications are permitted (115). The AME is asked to warn the pilots, who intend on participating in aerobatic flight, that the use of β-blockers and some of the calcium channel agents may predispose them to syncope during maneuvers that involve G-loading.

FAA policy once stated that if a medication was being used by physicians for a non–Federal Drug Agency recommended use, it was unacceptable for use in flight. This policy was changed in 2005, initially for the treatment of the dysmetabolic syndrome. Individuals with this syndrome are overweight, have hypertriglyceridemia and hypertension, and are prone to the development of diabetes mellitus. Clinical trials have demonstrated that the use of some oral hypoglycemic agents lessen insulin resistance and reduce the likelihood of diabetes developing. The oral hypoglycemic agents metformin, pioglitazone, and rosiglitazone, which are recommended by the FDA for treatment of type 2 diabetes mellitus, are being used to treat this condition. This treatment is not FDA approved. However, as these medications are already acceptable to the FAA, and becausethe dysmetabolic syndrome does not affect safety of flight, the FAA decided to accept their use although they are being utilized in a non–FDA approved situation.

A new concern is the use of alternative medicines such as herbals for treatment of a variety of conditions. Research on the effect of many of these substances is lacking; therefore, specific advice is sometimes difficult to provide for aeronautical personnel. The FAA at this time does not encourage or prohibit use of these alternative medicines by individuals engaged in aeronautical activities. However, applicants found to be utilizing them may be asked to provide additional information in order to determine their suitability for aeromedical certification.

Lastly, stimulants and anorexiants used for the treatment of attention deficit disorder or exogenous obesity, for example, amphetamines, methylphenidate, atomoxetine, phentermine, phendimetrazine, and sibutramine, are generally not permitted in aviation (124).

AIR TRAFFIC CONTROLLERS: A UNIQUE SUBSET OF CIVILIAN AVIATION PERSONNEL

Civilian air traffic controllers represent a very unique subset of aviation personnel in the United States. The type or authority for their medical certification depends on their employer. The principal employer, but not the only one, of civilian air traffic controllers in the United States is the FAA. Other organizations such as the DoD, county or city governments, and private contractors may also employ civilian controllers as air traffic control tower operators. At the time of this publication some 20,523 journeymen and supervisory controllers were employed by the FAA and an undetermined, but smaller number, were working for other employers. FAA controllers are employed in a variety of Federal facilities, which include but are not limited to enroute air traffic control centers (ARTCC), terminal radar control centers (TRACON), air traffic control towers (ATCT), automated flight service stations (AFSS), and combined enroute and approach centers (CERAP). Unlike their FAA counterparts, other civilian controllers perform duties only at select ATCT.

Civilian non-FAA controllers must meet at least Part 67 second-class medical standards. The requirements for a second-class medical certificate have already been discussed and are the same as for any pilot or flight crewmember holding the same class of medical certificate. No distinction is made for the fact that controllers do not fly in performing their safety-related duties. Civilian DoD controllers typically are issued medical certificates under applicable military controller standards for the particular service that employs them; those standards are covered elsewhere in this textbook. However, in cases where these controllers may be involved in dual civil and military air traffic control operations, they are required to hold at least a second-class FAA medical certificate in addition to whatever requirement the DoD might impose. Under Part 65 of the FAR, active duty military controllers are exempted from having to meet FAA medical standards.

Controllers employed by the FAA are referred to as *air traffic control specialists* and are held to medical standards contained in FAA Order 3930.3A, which is internal agency policy and not subject to the same rulemaking provisions of the FAR. As with military controllers, Part 65 of the FAR exempts FAA ATCS from having to meet FAA second-class medical standards. However, the standards imposed by Order 3930.3A are somewhat more stringent than the requirements for a second-class medical certificate under Part 67. The primary differences in the medical standards apply to hearing, vision, and blood pressure requirements; frequency at which examinations are performed based on age; need for electrocardiograms; and the provisions for medical clearances and waivers. Table 11-7 contains a summary of the FAA medical standards for agency air traffic controllers as specified in Order 3930.3A.

FAA ATCS medical standards have been categorized in a way that reflects the nature of air traffic activity at different air traffic control (ATC) facilities. The most stringent standards apply to those controllers in actual control of aircraft (i.e., ARTCC, CERAP, TRACON, and ATCT), whereas less restrictive standards apply to those controllers in AFSS facilities because they do not control air traffic. AFSS activities are typically limited to weather briefings, flight following, and flight planning for general aviation; these individuals never provide direct air traffic control services.

SPACE: THE NEXT CHALLENGE FOR MEDICAL CERTIFICATION

In February 1984, the President issued an Executive Order assigning the DOT as the lead Federal agency for the oversight of all commercial space launch operations in the United States. The Commercial Space Launch Act of October 30, 1984 was enacted by Congress to give DOT the necessary authority to regulate all commercial space launch operations in the United States. Initially the DOT was tasked with overseeing this activity; however, on November 16, 1995, this function was transferred to the FAA. The Secretary of Transportation delegated to the FAA the responsibility to license and regulate all U.S. commercial space launch activities to ensure that they are conducted safely and responsibly, and to promote, encourage, and facilitate commercial space transportation. Within the FAA, the Office of Commercial Space Transportation was tasked with carrying out this responsibility consistent with public health and safety, safety of property, and the national security and foreign policy interest of the United States.

On October 4, 2004, Space Ship One developed by Scaled Composites became the first private, piloted spacecraft, to exceed an altitude of 328,000 ft (99.974 4 km) twice within the span of a 14-day period, thereby claiming the $10 million Ansari X-Prize. The civilian astronauts who flew this vehicle were medically certified with an FAA second-class examination.

The current plan by the Office of the Federal Air Surgeon is to use the Special Issuance process to determine eligibility to pilot one of these aircraft in space should a pilot have a disqualifying medical condition.

The advent of manned space missions in the 1960s brought into play a new set of considerations in medical certification of aeronautical personnel. Medical standards had to be developed (and are discussed elsewhere in this textbook) to fit the requirements for those particular missions. However, the commercialization of space for activities such as manufacturing and tourism has forced a rethinking of some of these standards. Not everyone expected to travel to space will need to meet the stringent requirements imposed on NASA civilian personnel and military crews currently flying the space shuttle or assigned to the International Space Station.

Ordinary citizens will soon be venturing into regions once reserved only for the most physically fit individuals. With this in mind, and anticipating the development of commercial space travel, the FAA's Office of Aviation Medicine developed medical standards for space crews and passengers in 1999. These have yet to be finalized and approved.

National Aeronautics and Space Administration Medical Standards

The NASA has selected astronauts since the late 1950s and has continuously improved the medical selection process over the last 50 years. From 1959 until 1977, astronaut applicants were evaluated medically and ranked in terms of health and physical fitness against other applicants without a specific set of "pass–fail" medical standards (125). In 1977, a set of medical selection standards were developed for the NASA astronaut selection process. Standards were developed to

TABLE 11-7

Summary of Federal Aviation Administration (FAA) Air Traffic Control Specialists (ATCS) Medical Standards—FAA Order 3930.3A

ATCS Activity *Medical Standards*	*ATCT*	*ARTCC, TRACON, CERAP*	*AFSS*
Distant and near vision	20/20 or better in each eye separately, with or without correction		20/20 or better in at least one eye, with or without correction
Ocular motility	Normal in all quadrants, both eyes		No requirements
Intermediate vision	No requirements specified		
Color vision	Normal color vision		
Field of vision	Normal central and peripheral vision		Normal central vision
Phorias	No esophoria or exophoria >10 prism diopters No hyperphoria >1.5 prism diopter		No diplopia
Hearing	Pure tone audiometric test, unaided, with thresholds no worse than: Frequency (Hz): 500 1,000 2,000 4,000 Better ear (dB): 20 20 20 40 Worse ear (dB): 25 25 25 40		
ENT	No ear disease or condition manifested by, or that may be reasonably expected to be manifested by, vertigo or a disturbance of speech or equilibrium		
Cardiovascular	No history of heart disease; no history of CVA/TIA		
Electrocardiogram	With preemployment physical, then at ages 40, 45, 50, and biennially after age 50		
Blood pressure (BP)	Age Maximum reclining	BP (mm Hg) 140/90 150/90 150/100	
	50+	160/100	
General medical	No history of diabetes mellitus, epilepsy, other seizures, loss of consciousness, and no other functional or organic condition that may indicate a potential hazard to safety while performing air traffic control duties		
Psychiatric	No diagnoses of depression, anxiety, psychosis, bipolar disorder, or severe personality disorder		
Substance dependence or substance abuse	A diagnosis or medical history of substance dependence or abuse is disqualifying unless there is a established clinical evidence of recovery, including sustained total abstinence from the substance(s); guidance in DOT Order 3910.1C		
Disqualifying conditions	Unlike Part 67 (Table 3), no specifically disqualifying conditions are listed in the Order; however, the same disqualifying conditions that apply to Part 67 medical certificate holders typically apply to FAA ATCS; each case is reviewed individually		
Examination frequency			
Those younger than 40 yr	Every 2 yr		Every 3 yr
Those aged 40 or older	Every year		Every 2 yr

ENT, ears, nose, throat; CVA, cerebrovascular accident; TIA, transient ischemic attack.

select individuals able to perform space flight duties at the time of selection and for a 10- to 15-year career. These initial standards included Class I for pilots and Class II for mission specialists. Some of the medical standards (e.g., vision) were less stringent for Class II; 35 astronauts were chosen that year including 22 mission specialists. Payload specialist standards (Class III) were developed in the early 1980s to provide for selection of non–career astronauts who were selected for specific missions due to their unique science or career backgrounds.

Payload specialists flew as early as 1983 on Spacelab 1 (STS-9). Since that time, 59 payload specialists have flown—among them former Senator Jake Garn, former Congressman and Senator Bill Nelson, and former astronaut and Senator John Glenn. Two payload specialists have flown three times on the space shuttle, Chiaki Mukai from Japan flew on, STS 47, STS 65, and STS 95, and Charlie Walker, McDonald Douglas, flew on STS 41, STS 51, and STS 61. Christa McAuliffe was selected as the first *teacher in space* and flew on STS 51-L. She was selected using payload specialist standards. Seven astronauts including Christa McAuliffe died in the Challenger accident on January 28, 1986. Her backup was Barbara Morgan, who returned to teaching after the Challenger accident, and subsequently became a NASA mission specialist in 1998. She is scheduled to fly in space aboard STS-118.

Class IV medical standards were developed in the mid-1980s in anticipation of flying ordinary citizens in space but were not used. The flights of Senator Garn and then Congressman Nelson, and Ms. Christa McAuliffe, fit that category (although payload specialist standards were used), and more flights were planned such as for journalists before the Challenger accident. Flights with ordinary citizens onboard were stopped after this accident. Recently, with the addition of civilians who pay for a trip to the International Space Station (ISS), NASA Class IV medical standards were used by the ISS International Partners to develop a new set of medical standards for Space Flight Participants (SFPs) similar to the earlier concept of flying ordinary citizens in space.

NASA medical standards for selection and retention have undergone several revisions since 1978, the most recent being in 2006 to 2007. As new medical knowledge is gained, standards may be relaxed on the basis of an improved evidence base underlying the standard. New mission demands, however, such as flying for longer periods to the ISS or for exploration missions, may drive standards that are more conservative. Standards that are more conservative might prevent the potential mission impact of a medical problem. New medical standards are about to be published at the time of this writing (126). A second volume covering medical evaluations is under development. These standards apply to the selection and retention standards and evaluations for all space flight categories, and represent the most current updates to the standards that were first published in 1978. These updated standards will be used for any future astronaut selections.

Finalist candidates for an astronaut selection are brought to the Johnson Space Center for 1 week of interviews and medical examinations. In the past, approximately 20 candidates were examined in a given week and the total number of finalists reached 120 or more. These numbers may change for future selections. In addition to a rigorous history, physical, and laboratory examination, experts in ophthalmology, otolaryngology, obstetrics and gynecology, neurology, and psychiatry and psychology also conduct specialist examinations. An Aerospace Medicine Board (AMB) at NASA reviews the candidates and determines their eligibility based on the most recently approved version of the NASA medical standards. Final class sizes have varied on the basis of the skills NASA needed during a particular selection process. After selection, all NASA astronauts undergo an annual medical and laboratory examination for continuation of flight status. The AMB hears cases that deviate from the standards to determine if a temporary or permanent waiver is required. Permanent waivers are reviewed and concurred in by the Chief Health and Medical Officer at NASA headquarters.

Additional standards were developed for long-duration flights to the ISS for all crewmembers (astronauts, cosmonauts, and SFPs) who fly to the ISS. These volumes were developed and approved by all five international partners on the ISS including NASA and the space agencies of Canada (Canadian Space Agency or CSA), Russia (Roscosmos), Japan (the Japan Aerospace Exploration Agency or JAXA), and the European Space Agency (ESA) that represents 17 countries. These additional standards are specified in a selection and periodic examination volume (127); additional examinations for mission-assigned crewmembers are specified in a separate volume (128). Tests that are required for long-duration flight (>30 days) aboard the ISS include behavioral health examinations and screening tests such as electron beam computed tomography (EBCT), MRI, ultrasound examinations, colonoscopy, and tests for *Helicobacter pylori*. The partners present all astronauts and cosmonauts to a Multilateral Space Medicine Board (MSMB) that considers the flight qualification of anyone who flies to the ISS. Annual recertification of short- and long-duration flight status is determined by the MSMB after being first evaluated and approved by the sponsoring agency's medical board. Monthly telecons are conducted as well as two face-to-face meetings each year.

A specific set of standards was developed internationally for SFPs, essentially space tourists (129). These standards are not as stringent as those for career astronauts and cosmonauts, and are planned for public release to assist the emerging commercial space flight business. As of this writing, these standards may be released as early as fall 2007. SFPs who have flown include Dennis Tito, Mark Shuttleworth, Gregory Olsen, Anousheh Ansari, and Charles Simonyi as recently as April 2007. These SFPs pay for the space flight and training, launch and land in Soyuz spacecraft, and spend 10 days in orbit on the ISS. Evaluations for SFPs occur first in Russia at the Institute of Biomedical Problems (IBMP), and the candidate is approved by the Roscosmos Chief Medical Commission before presentation to the MSMB.

Since 2005, NASA has also been formulating in-flight crew health standards to guide the maintenance of health of astronauts from the deleterious effects of space flight including microgravity, closed-cabin exposures to toxins and microorganisms, and environmental exposure to ionizing radiation. These standards also guide biomedical research for the development of countermeasures to microgravity, and guide the design of health care systems and environmental systems. These standards cover all aspects of human systems for space flight; volume 1 specifies permissible exposure limits (e.g., radiation) along with permissible outcome limits (e.g., bone loss), fitness for duty (e.g., behavioral health), and levels of medical care to design health care systems appropriate to the mission risk (130); volume 2 addresses environmental health issues such as acceptable limits for ionizing and nonionizing radiation, air and water toxicologic and microbiologic contaminants, and acceleration, acoustics and vibration. Human factors standards are used to design spacecraft and habitat architectures, equipment, and human–system interfaces, as well as for extravehicular activity (EVA) (131). Volume 1 of these standards is approved as an Agency set of standards; volume 2 is undergoing the approval cycle at the time of this writing. These standards have allowed NASA to design a "standards to deliverables" process: a focused, risk management system that guides the development of effective and efficient mitigation strategies.

CONCLUSION AND ADDITIONAL RESOURCES

Given the significant growth expected in aerospace activity in the coming decades, it is clear that the challenges for medical certification of aeronautical personnel are, and will be, substantial. Aerospace medicine practitioners will be constantly challenged to determine the safety impact of medical conditions, new therapies and treatments, and new medications. Issues that arise must be quickly researched and resolved in order to keep pace with rapid medical developments. Through innovative changes in program administration and careful application of research, the challenges must be met in a manner that will not only provide as many individuals as possible the ability to obtain and maintain aeromedical certification but also continue to ensure safety in aviation and commercial space travel.

A variety of references are available to assist the flight surgeon or aviation medical examiner in making decisions concerning medical certification, fitness for duty, and assessment of impairment and disability. In addition to the FAA *Guide for Aviation Medical Examiners* (117), these include guides for aviation medical examiners published by other national civilian and military authorities, some of which are available online (132), clinical practice guidelines published by the American Society of Aerospace Medicine Specialists, and Rayman's Clinical Aviation Medicine, fourth edition (133).

ACKNOWLEDGMENTS

The authors wish to acknowledge contributions by Dr. Elliot Rosenberg concerning parts of the section on Factors Influencing Aircrew Health, and by Dr. Jeff Davis for the section on NASA Medical Standards.

REFERENCES

1. Lyons T, Neel RL, Simpson CG, et al. East meets West: a comparison of eastern block/western aeromedical practices. *Aviat Space Environ Med* 1997;68:1150–1153.
2. Bento Coelho J, Ferreira A, Serrano J, et al. Noise assessment during aircraft run-up procedures. *Aviat Space Environ Med* 1999;70: A22–A26.
3. Kikukawa A, Tachibana S, Yagura S. G-related musculoskeletal spine symptoms in Japan Air Self Defense Force F-15 pilots. *Aviat Space Environ Med* 1995;66:269–272.
4. Nakagawara V, Montgomery RW. Laser pointers and aviation safety. *Aviat Space Environ Med* 2000;71:1060–1062.
5. Oksa J, Hamalainen O, Rissanen S, et al. Muscle strain during aerial combat maneuvering exercise. *Aviat Space Environ Med* 1996;67: 1138–1143.
6. Coakwell MR, Bloswick DS, Moser R Jr, et al. High-risk head and neck movements at high G and interventions to reduce associated neck injury. *Aviat Space Environ Med* 2004;75:68–80.
7. International Civil Aviation Organization. *Manual on laser emitters and flight safety*. International Civil Aviation Organization (ICAO), 2003.
8. Association AT. *Airline cabin air quality*. Washington, DC: ATA, 1994.
9. Lindgren T, Norback D, Lindgren T, et al. Health and perception of cabin air quality among Swedish commercial airline crew. *Indoor Air* 2005;15(Suppl 10):65–72.
10. Lindgren T, Norback D, Andersson K, et al. Cabin environment and perception of cabin air quality among commercial aircrew. *Aviat Space Environ Med* 2000;71:774–782.
11. National Research Council CoAQiPCoCA. *The airliner cabin environment and the health of passengers and crew*. Washington, DC: National Academy Press, 2002.
12. Finkelstein S. The 17th Andre Allard Memorial Lecture: to smoke or not to smoke in civil aviation. *Aviat Space Environ Med* 1998;69: 415–416.
13. Lindgren T, Norbäck D, Wieslander G. Perception of cabin air quality in airline crew related to air humidification, on intercontinental flights. *Indoor Air* 2007;17:204–210.
14. Wenzel R. Airline travel and infection [editorial comment]. *N Engl J Med* 1996;334:981–982.
15. Nagda N, Koontz MD, Konheim AG, et al. Measurements of cabin air quality aboard commercial airliners. *Atmos Environ* 1992;26A: 2203–2210.
16. Thibeault C. Airliner cabin air quality. *Occup Med* 2002;17:279–292.
17. Thibeault C, Thibeault C. Aerospace Medical Association. Cabin air quality. *Aviat Space Environ Med* 1997;68:80–82.
18. Markel H, Gostin LO, Fidler DP. Extensively drug-resistant tuberculosis: an isolation order, public health powers, and a global crisis. *JAMA* 2007;298:83–86.
19. Leder K, Newman D, Leder K, et al. Respiratory infections during air travel. *Intern Med J* 2005;35:50–55.
20. WHO. *Tuberculosis and air travel: guidelines for prevention and control*. 2006.
21. James M, Green R. Airline pilot incapacitation survey. *Aviat Space Environ Med* 1991;62:1068–1072.
22. Conlon C, Berendt AR, Dawson K, et al. Runway malaria [letter] [see comments]. *Lancet* 1990;335:472–473.
23. Gratz NG, Steffen R, Cocksedge W, et al. Why aircraft disinsection? [see comment]. *Bull World Health Organ* 2000;78:995–1004.
24. Rayman RB, Rayman RB. Aircraft disinsection. *Aviat Space Environ Med* 2006;77:733–736.
25. Ellis RA. AGARD. *Aircraft disinsection: a guide for military & civilian air carriers*. In: ed. France: Neuilly-Sur-Seine, 1996.
26. Anderson FM, Tarlock AD. *Hazardous waste environmental protection: law and policy*. Boston: Little, Brown and Company, 1984.
27. Voge V, Tolan G. Physiological problems caused by transportation of hazardous cargo in military aircraft. *Aviat Space Environ Med* 1993;64:662–665.
28. Voge V, Tolan G. Hazardous materials incidents in military aircraft. *Aviat Space Environ Med* 1993;64:658–661.
29. National Transportation Safety Board. *Aircraft accident report: in-flight fire and impact with terrain, Valujet Airlines Flight 592*. In: ed. NTSB,1996.
30. Odenheimer G. Function, flying, and the Age-60 rule [editorial comment]. *J Am Geriatr Soc* 1999;47:910–911.
31. Tilton F. Should the FAA change it's Age-60 Rule? *Fed Air Surg Med Bull* 2007:2; Fall.
32. Yesavage J, Taylor JL, Mumenthaler MS, et al. Relationship of age and simulated flight performance [see comments]. *J Am Geriatr Soc* 1999;47:819–823.
33. Helmreich R. On error management: lessons from aviation. *Br Med J* 2000;320:781–785.

34. Sexton J, Thomas EJ, Helmreich RL. Error, stress, and teamwork in medicine and aviation: cross sectional surveys. *Br Med J* 2000;320:745–749.
35. Wiegmann D, Shappell SA. Human error and crew resource management failures in Naval aviation mishaps: a review of US Naval Safety Center data, 1990–1996. *Aviat Space Environ Med* 1999;70:1147–1151.
36. Iglesias R, Terres A, Chavarria A. Disorders of the menstrual cycle in airline stewardesses. *Aviat Space Environ Med* 1980;51:518–520.
37. Heaps C, Fischer MD, Hill RC. Female acceleration tolerance: effects of menstrual state and physical condition. *Aviat Space Environ Med* 1997;68:525–530.
38. McGinnis J, Foege WH. Actual causes of death in the United States. *JAMA* 1993;270:2207–2212.
39. Fitzpatrick D, Shannon S. Health-risk behaviors of Army aircrew. *J Occup Med* 1992;34:810–814.
40. USAFSAM. *USAF flight surgeon's guide*, Chapter 14. San Antonio, 1999:23.
41. Grossman A, Landau DA, Barenboim E, et al. Smoking cessation therapy and the return of aviators to flying duty. *Aviat Space Environ Med* 2005;76:1064–1067.
42. Henningfield JE, Rose CA, Henningfield JE, et al. How US airlines became smoke free? *Tob Control* 2001;10:295–296.
43. International Civil Aviation Organization. *Resolution A29-15: smoking restrictions on international passenger flights*. Available at: http://www.icao.int/cgi/goto_m_med.pl?icao/en/med/MED_Resolutions.html, 1992.
44. Civil Aerospace Medical Institute. *Alcohol and flying, a deadly combination*. Oklahoma City: Civil Aviation Medical Institute, FAA, 1994.
45. Substance Abuse and Mental Health Services Administration (SAMHSA) Office of Applied Studies. *Substance use and mental health characteristics by employment status*. Rockville: Substance Abuse and Mental Health Services Administration, 1999.
46. Cook R, Bernstein AD, Andrews CM. *Assessing drug use in the workplace: a comparison of self-report, urinalysis, and hair analysis, NIDA research monograph*. NIDA, 1997:247–272.
47. Cook C. Alcohol and aviation. *Addiction* 1997;92:539–555.
48. Kraus CK, Li G, Kraus CK, et al. Pilot alcohol violations reported in U.S. newspapers, 1990–2006. *Aviat Space Environ Med* 2006;77:1288–1290.
49. Billings C, Wick RL Jr, Gerke RJ, et al. Effects of ethyl alcohol on pilot performance. *Aerosp Med* 1973;44:379–382.
50. Billings C, Demosthenes T, White TR, et al. Effects of alcohol on pilot performance in simulated flight. *Aviat Space Environ Med* 1991;62:233–235.
51. Tornros J, Laurell H. Acute and hang-over effects of alcohol on simulated driving performance. *Blutalkohol* 1991;28:24–30.
52. Knowles J, Laverty SG, Kuechler HA. Effects on REM sleep. *Q J Stud Alcohol* 1968;29:342–349.
53. Gibbons H. Alcohol, aviation, and safety revisited: a historical review and a suggestion. *Aviat Space Environ Med* 1988;59:657–660.
54. Taasan V, Block AJ, Boysen PG, et al. Alcohol increases sleep apnea and oxygen desaturation in asymptomatic men. *Am J Med* 1981;71:240–245.
55. Canfield D, Hordinsky J, Millett DP, et al. Prevalence of drugs and alcohol found in fatal civil aviation accidents between 1994 and 1998. *Aviat Space Environ Med* 2001;72:120–124.
56. Bray R, Sanchez RP, Ornstein ML. *1998 Department of defense survey of health related behaviors among military personnel*. Research Triangle Park: Research Triangle Institute, 1995.
57. Bray RM, Rae Olmsted KL, Williams J, et al. Progress toward healthy people 2000 objectives among U.S. military personnel. *Prev Med* 2006;42:390–396.
58. Bray RM. *2005 Department of defense survey of health related behaviors among active duty military personnel*. 2006.
59. Taylor J, O'Hara R, Mumenthaler MS, et al. Relationship of CogScreen-AE to flight simulator performance and pilot age. *Aviat Space Environ Med* 2000;71:373–380.
60. Canfield DF, Hordinsky J. Medicine OoA. *Drugs and alcohol found in fatal civil aviation accidents between 1989 and 1993*. In: ed. Washington DC: Federal Aviation Administration, 1995.
61. Kruyer W. Cardiology. In: Russell Rayman M, ed. *Clinical aviation medicine*. New York: Castle Conolly Graduate Medical Publishing, LLC, 2000:164–165.
62. USAF. *Health promotion program*, Air Force Instruction AFI 40-101. 1998.
63. US Department of the Army. *Army health promotion*, Army Regulation AR 600-63. 1996.
64. US Navy. *OPNAV 6100.2A Health and Wellness Promotion Program*. 2007.
65. Billings CE, Billings CE. Epidemiology of injuries and illnesses during the United States Air Force Academy 2002 Basic Cadet Training program: documenting the need for prevention. *Mil Med* 2004;169:664–670.
66. Qiang Y, Li G, Rebok GW, et al. Body mass index and cardiovascular disease in a birth cohort of commuter air carrier and air taxi pilots. *Ann Epidemiol* 2005;15:247–252.
67. Poston WS, Haddock CK, Peterson AL, et al. Comparison of weight status among two cohorts of US Air Force recruits. *Prev Med* 2005;40:602–609.
68. Katz D. *Nutrition in clinical practice: a comprehensive, evidence-based manual for the practitioner*. Baltimore: Lippincott Williams & Wilkins, 2000.
69. Alpers DS, Bier DM. *Manual of nutritional therapeutics*. Boston: Little, Brown and Company, 1995.
70. Kaufman W, Callin GD, Harris CE. Energy expenditure of pilots flying cargo aircraft. *Aerosp Med* 1970;41:591–596.
71. Littell D, Joy RT. Energy cost of piloting fixed and rotary wing aircraft. *J Appl Physiol* 1969;26:26.
72. Lorentzen F. Oxygen consumption during flight at moderate G. *Aerosp Med* 1965;36:415–417.
73. Hastings J. Neurology. In: Rayman R, ed. *Clinical aviation medicine*. New York: Castle Conolly Graduate Medical Publishing, LLC, 2000:164–165.
74. York E, Mitchell RE, Graybiel A. Cardiovascular epidemiology, exercise, and health: 40-year follow-up of the US Navy's "1000 aviators." *Aviat Space Environ Med* 1986;57:597–599.
75. MacIntyre NR, Mitchell RE, Oberman A, et al. Longevity in military pilots: 37-year followup of the Navy's "1000 aviators." *Aviat Space Environ Med* 1978;49:1120–1122.
76. Pukkala E, Auvinen A, Wahlberg G. Incidence of cancer among Finnish airline cabin attendants, 1967–92 [see comments]. *Br Med J* 1995;311:649–652.
77. Clark D, Tolan GD, Johnson R, et al. The West Point Study: 40 years of follow-up. *Aviat Space Environ Med* 1994;65:A71–A74.
78. Grayson J, Lyons TJ. Cancer incidence in United States Air Force aircrew, 1975–89 [see comments]. *Aviat Space Environ Med* 1996;67:101–104.
79. McCrary BF, Van Syoc DL, McCrary BF, et al. Permanent flying disqualifications of USAF pilots and navigators (1995–1999). *Aviat Space Environ Med* 2002;73:1117–1121.
80. Preston F. Physiological problems in air cabin crew. *Proc R Soc Med* 1974;67:825–829.
81. Lavernhe J, Pasquet J, Mathivat A. Incidence of cardiovascular diseases among the flight deck personnel of an airline. *Aerosp Med* 1969;40:62–63.
82. Kidera G. Clinical aspects of commercial aviation medicine. *JAMA* 1967;201:242–246.
83. Orford R, Carter ET. Preemployment and periodic physical examination of airline pilots at the Mayo clinic, 1939–1974. *Aviat Space Environ Med* 1976;47:180–184.

84. Holt G, Taylor WF, Carter ET. Airline pilot disability: the continued experience of a major US airline. *Aviat Space Environ Med* 1985;56:939–944.
85. Band P, Spinelli JJ, Ng VT, et al. Mortality and cancer incidence in a cohort of commercial airline pilots. *Aviat Space Environ Med* 1990;61:299–302.
86. Band P, Le ND, Fang R, et al. Cohort study of Air Canada pilots: mortality, cancer incidence, and leukemia risk. *Am J Epidemiol* 1996;143:137–143.
87. Band P, Deschamps M, Fang R, et al. Long-term disability rates in a cohort of Air Canada pilots. *Aviat Space Environ Med* 1998;69:1137–1140.
88. Irvine D, Davies DM. The mortality of British Airways pilots, 1966–1989: a proportional mortality study. *Aviat Space Environ Med* 1992;63:276–279.
89. Irvine D, Davies DM. British Airways flight deck mortality study, 1950–1992. *Aviat Space Environ Med* 1999;70:548–555.
90. Besco R, Sangal SP, Nesthus TE, et al. Institute CA. *A longevity and survival analysis for a cohort of retired airline pilots*. In: ed. FAA, 1995.
91. Nicholas JBG, Padgett S, Hoel D, et al. Women on the flight deck—disease prevalence among female airline pilots in four us airlines. *Ann Epidemiol* 2002;12:511.
92. Nicholas JS, Butler G, Hoel DG, et al. Breast cancer in female airline pilots. *Epidemiology* 2003;14:S63.
93. Ballard T, Lagorio S, De Angelis G, et al.A cancer incidence and mortality among flight personnel: a meta-analysis. *Aviat Space Environ Med* 2000;71:216–224.
94. Nicholas J, Lackland DT, Dosemeci M Jr, et al. Mortality among US commercial pilots and navigators. *J Occup Environ Med* 1998;40:980–985.
95. Blettner M, Zeeb H, Auvinen A, et al. Mortality from cancer and other causes among male airline cockpit crew in Europe. *Int J Cancer* 2003;106:946–952.
96. Buley L. Incidence, causes and results of airline pilot incapacitation while on duty. *Aerosp Med* 1969;40:64–70.
97. Chapman P. The consequences of in-flight incapacitation in civil aviation. *Aviat Space Environ Med* 1984;55:497–500.
98. Booze C Jr. Sudden in-flight incapacitation in general aviation. *Aviat Space Environ Med* 1989;60:332–335.
99. Froom P, Benbassat J, Gross M, et al. Air accidents, pilot experience, and disease-related in-flight sudden incapacitation. *Aviat Space Environ Med* 1988;59:278–281.
100. Masters R. Aeromedical Support to Airline and Civilian Aircrew. In: ed. *Fundamentals of aerospace medicine*. Baltimore: Lippincott-Raven, 1996:775.
101. DeJohn CA, Wolbrink AM, Larcher JG, et al. In-flight medical incapacitation and impairment of airline pilots. *Aviat Space Environ Med* 2006;77:1077–1079.
102. Mitchell SJ, Evans AD, Mitchell SJ, et al. Flight safety and medical incapacitation risk of airline pilots. *Aviat Space Environ Med* 2004;75:260–268.
103. Kulak L, Wick RL Jr, Billings CE. Epidemiological study of in-flight airline pilot incapacitation. *Aerosp Med* 1971;42:670–672.
104. Lynge E. Risk of breast cancer is also increased among Danish female airline cabin attendants [letter comment] [see comments]. *Br Med J* 1996;312:253.
105. Wartenberg D, Stapleton CP. Risk of breast cancer is also increased among retired US female airline cabin attendants [letter comment] [see comments]. *Br Med J* 1998;316:1902.
106. Linnersjo A, Hammar N, Dammstrom BG, et al. Cancer incidence in airline cabin crew: experience from Sweden [see comment]. *Occup Environ Med* 2003;60:810–814; [Erratum appears in *Occup Environ Med* 2004;61(1):94.]
107. Haldorsen T, Reitan JB, Tveten U, et al. Cancer incidence among Norwegian airline cabin attendants [see comment]. *Int J Epidemiol* 2001;30:825–830.
108. Blettner M, Zeeb H, Langner I, et al. Mortality from cancer and other causes among airline cabin attendants in Germany, 1960–1997. *Am J Epidemiol* 2002;156:556–565.
109. Cone J, Vaughan LM, Huete A, et al. Reproductive health outcomes among female flight attendants: an exploratory study. *J Occup Environ Med* 1998;40:210–216.
110. Aspholm R, Lindbohm ML, Paakkulainen H, et al. A spontaneous abortions among Finnish flight attendants. *J Occup Environ Med* 1999;41:486–491.
111. Irgens A, Irgens LM, Reitan JB, et al. Pregnancy outcome among offspring of airline pilots and cabin attendants. *Scand J Work Environ Health* 2003;29:94–99.
112. Agredano YZ, Chan JL, Kimball RC, et al. Accessibility to air travel correlates strongly with increasing melanoma incidence. *Melanoma Res* 2006;16:77–81.
113. Rafnsson V, Hrafnkelsson J, Tulinius H, et al. Risk factors for cutaneous malignant melanoma among aircrews and a random sample of the population [see comment]. *Occup Environ Med* 2003;60:815–820.
114. Takahashi G. International aviation medicine. In: DeHart RL, Davis JR, eds. *Fundamentals of aerospace medicine*. Baltimore: Williams & Wilkins, 2002:586–587.
115. Preston E. *FAA historical chronology: civil aviation and the federal government, 1926–1996*. Washington, DC: Federal Aviation Administration, 1998.
116. Holbrook HA. *Civil aviation in the beurocracy*. Bethesda: Banner Publishing Company, 1974.
117. Burton R. G-induced loss of consciousness: definition, history, current status. *Aviat Space Environ Med* 1988;59:2–5.
118. Civil Aerospace Medical Institute, Office of Aviation Medicine CAI. *Guide for aviation medical examiners*. In: ed. Washington, DC: Federal Aviation Administration, 1999.
119. US Department of Transportation FAA. *Federal register; revisions of airman medical standards and certification procedures and duration of medical certificates*; Final Rule:11238–11255.
120. Civil Aerospace Medical Institute. *Guide for aviation medical examiners*. Available at: http://www.faa.gov/about/office_org/headquarters_offices/avs/offices/aam/ame/guide/.
121. Personal communication from AME staff. *Aeromedical education division*. Oklahoma City: CAMI, February 1, 2001.
122. Civil Aerospace Medical Institute. *Aeromedical certification statistical handbook*. AC8500-1. Oklahoma City: Office of Aviation Medicine, Civil Aerospace Medical Institute, FAA, 2000.
123. Civil Aerospace Medical Institute. *Oklahoma city*. Civil Aerospace Medical Institute, Federal Aviation Administration, 2005.
124. Silberman WS. RK and laser visual acuity procedures. *Fed Air Surg Bull* 1998;98(3):5.
125. Silberman WS. Aeromedical certification update. *Fed Air Surg Bull* 2000;Summer:3.
126. Civil Aerospace Medical Institute. *Oklahoma City*. Civil Aerospace Medical Institute, Federal Aviation Administration, 2006.
127. Bourge RC. In: Bennett JC, Goldman L, eds. *Heart transplant*. Philadelphia: WB Saunders, 2000:377.
128. Silberman WS. Medications in civil airmen. *Fed Air Surg Bull* 1997;97(4):10.
129. Virtual Flight Surgeons. Available at: http://www.aviationmedicine.com/content/index.cfm?fuseaction=showContent&contentID=103&navID=103. Accessed April, 2007.
130. Rayman RB, Hastings JD, Kruyer WB, et al. *Clinical aviation medicine*. New York: Professional Publishing Group, 2006.

CHAPTER 12

Respiratory Diseases: Aeromedical Implications

Jeb S. Pickard and Gary W. Gray

> And the Lord God formed man of the dust of the ground, and breathed into his nostrils the breath of life . . . *Genesis 2:7.*

With their elastic support structure, the lungs are the organ most susceptible to distortion and damage from radial accelerative forces, and have been described as the "Achilles' heel" of man in the gravito-inertial environment (1). The primary function of the lungs is gas exchange, the efficiency of which depends on appropriate matching of inspired gas with pulmonary perfusion. The distribution of both ventilation and perfusion is affected by gravitational and radial accelerative forces even in healthy lungs. Life support equipment for new generation agile fighters incorporates positive pressure breathing (PPB) to increase G tolerance [positive pressure breathing for G protection (PPG)], and to maintain alveolar oxygen tension during decompression (PPB), adding additional stress to pulmonary tissue. Along with the skin, the lungs form the primary interface to the gaseous and particulate environment, and are susceptible to acute and long-term damage from environmental contamination, an increasing concern as space travel extends from low earth orbit to lunar and interplanetary destinations.

Diseases which affect respiratory structure and function increase the susceptibility to damage and dysfunction in the aviation environment, increasing the aeromedical concern with respect to acute incapacitation, hypoxia, acceleration atelectasis, and potential compromise of G tolerance (see also Chapter 4). In the high-G environment of military fighter operations, marked ventilation-perfusion ($\dot{V}/\dot{Q}$) mismatching occurs due to both gravitational and local/regional factors with resultant impairment of gas exchange. Small airway closure occurs even in the tidal breathing range and, with high-inspired oxygen tensions, can lead to rapid absorption distal to closed airways resulting in "acceleration atelectasis." Diseases which affect airway function (primarily obstructive lung disease—asthma, chronic bronchitis, and emphysema) are likely to aggravate $\dot{V}/\dot{Q}$ mismatching, further compromising gas exchange, potentially reducing G tolerance and increasing susceptibility to acceleration atelectasis. Because of the ubiquitous potential for hypoxia in the aviation environment, aggravation of hypoxia with resultant performance decrements or incapacitation is a more likely consequence of respiratory disease. Respiratory diseases may aggravate the risk and magnitude of hypoxia.

With the transition of space initiatives to lunar and in the longer term, interplanetary travel, the lungs may again become the "Achilles heel". The lung is the primary filter for lunar dust and other particulate matter to which space travelers are likely to be exposed. The physical, chemical, and potentially even biological properties of lunar and planetary dust are still largely unknown (see Chapter 10).

In this chapter, we will discuss the aeromedical implications of obstructive lung diseases including asthma and chronic obstructive pulmonary disease (COPD), pulmonary cysts and bullae, pneumothorax, and interstitial/restrictive lung diseases including sarcoidosis. Because the dominant sleep disorder is obstructive sleep apnea (OSA), sleep medicine is commonly managed by pulmonary specialists, and therefore key clinical sleep disorders will also be reviewed here. Sleep physiology, fatigue countermeasures, and circadian adaptation are discussed in Chapter 11 and Chapter 23.

ASSESSING AIRCREW WITH RESPIRATORY DISEASE

The standard assessment of individuals with respiratory problems should include pulmonary function testing and lung imaging. The assessment is geared toward defining the risk for hypoxia and for incapacitation due to respiratory distress. Much information may be derived from readily available, well standardized, and relatively noninvasive tests. The evaluation of sleep disorders, on the other hand, is more elaborate and time-consuming, utilizing diagnostic procedures that are not as well standardized across different laboratories.

Pulmonary Function Testing

Although a variety of esoteric tests can be performed in a fully equipped pulmonary function laboratory, a respiratory evaluation almost always begins with the forced vital capacity (FVC) maneuver, which is routinely, though somewhat imprecisely referred to as spirometry. When properly performed, spirometry can provide information about restrictive and obstructive diseases; a normal FVC essentially rules out restriction, while a reduced 1 second forced expiratory volume (FEV_1) expressed as a fraction of FVC (FEV_1/FVC) establishes the presence of obstruction. Obstruction may have a variety of causes, including the normal effects of aging, but repetition of the test may provide further information. A significant change in FEV_1 after administration of a bronchodilator, or after an interval of time, establishes reversible obstruction, which, in the absence of another identifiable cause, strongly suggests asthma.

A low FVC may be caused by a restrictive or obstructive process (due to air trapping, in the latter instance), and should be evaluated by lung volumes. Gas dilution methods are commonly available, but as with spirometry, air trapping can give rise to falsely reduced measurements of volume. Whole-body plethysmography is a far more accurate method for measuring lung volumes. The evaluation of restrictive disease often includes diffusing capacity (or transfer factor), which is complementary to arterial blood gas (ABG) analysis in evaluating $\dot{V}/\dot{Q}$ mismatching. However, diffusing capacity is sensitive to a number of confounding variables, and reproducibility is often problematic.

In an aviator, identification of chronic lung disease involving the lung parenchyma should prompt consideration of ABG measurement. ABG should also be measured in any individual with COPD. (Blood gas analysis is rarely indicated in an asthmatic because, except during a serious exacerbation, arterial saturation will usually be normal in all but the most severe asthmatics.) Aircraft cabin altitude is typically restricted to a maximum of 8,000 ft (2,438 m) for civilian aircraft, although certain military aircraft routinely maintain a cabin altitude of 10,000 ft (3,048 m). At those altitudes, an adult with normal cardiorespiratory status will have a resting arterial partial pressure of oxygen of approximately 60 mm Hg. With preexisting lung disease, the arterial partial pressure of oxygen may be further decreased. Measuring peripheral saturation by oximetry is not a satisfactory substitute for assessing oxygenation, because saturation does not appreciably fall until arterial partial pressure drops below 60 mm Hg. Affected aircrew with mild or moderate disease severity will usually be on the relatively flat portion of the oxyhemoglobin dissociation curve (see Figure 2.4).

The list of restrictive diagnoses outnumbers obstructive diseases, but obstructive disease is more commonly encountered in practice, and one disease in particular accounts for most pulmonary problems in aviation. The identification of obstruction on spirometry that shows a significant (>15%) improvement after a bronchodilator challenge is strong evidence for asthma, but asthma is a variable disease, and may not be evident at the time spirometry is performed. Where asthma is suspected despite normal spirometry, bronchial provocation testing (BPT) can be employed. A variety of provocative agents have been utilized in the laboratory, of which nebulized histamine and particularly methacholine are the best standardized. With methacholine challenge, the usual parameter measured is the PC20, the concentration of methacholine required to provoke a 20% reduction in FEV_1. A PC20 of less than 8 mg/mL has typically been considered positive. Alternatively, current American Thoracic Society guidelines recognize a borderline category (2). Under this classification, individuals with a PC20 equal to or greater than 16 mg/mL are considered normal, whereas the development of bronchospasm at concentrations lower than 4 mg/mL is considered hyperreactivity. Those who show a 20% drop in FEV_1 at concentrations between these limits are considered to be borderline. Although it is most often employed as a diagnostic maneuver in patients presenting in atypical manner, methacholine challenge testing can also be used to assess response to therapy. Because of the time and expense involved, the latter indication has not found wide acceptance in clinical practice, but demonstrating suppression of reactivity in response to treatment can be very useful in aircrew.

A few caveats are in order. BPT is not useful for screening; the prevalence of airway hyperreactivity considerably exceeds that of clinical asthma, and will fluctuate with other factors such as recent respiratory infections. The results of BPT must be integrated with the clinical picture. Also, methacholine challenge testing is not useful for ruling out subsequent relapse in remitted childhood asthmatics. In one recent study, approximately a third of those with negative bronchoprovocation tests subsequently relapsed (3). This is equivalent to the historical rate of relapse of remitted childhood asthma.

Imaging

The chest x-ray is indispensable in the evaluation of respiratory disease. The reason is simple enough; for many diseases, the lungs provide their own contrast medium. At full inspiration, the chest cavity is predominantly filled with air, and disease processes such as edema, inflammation, neoplasia, and fibrosis are associated with water density. The standard chest film is much less useful in the evaluation of obstructive diseases. The disruption of alveolar membranes typical of emphysema and the narrowing of endobronchial lumina seen in bronchitis and asthma do not appreciably affect the radiodensity of the lung.

Computed tomography (CT) of the chest significantly increases resolution, and better delineates adenopathy, early fibrosis, small nodules, and numerous other abnormalities. It provides much clearer imaging of bullae than does routine chest x-ray, and the use of a high-resolution format also allows the identification of subpleural blebs, something not possible with a standard roentgenogram.

Sleep Studies

Accurate diagnosis of most clinical sleep disorders requires overnight polysomnography (PSG). Although a full night's sleep study in a sleep disorders laboratory is cumbersome, simpler methods sacrifice too much information. Typically, PSG will include electroencephalography (two to three leads), electromyography (genioglossus and anterior tibialis), electrooculography, electrocardiography (usually lead II), and oximetry. Airflow and respiratory effort are the two respiratory parameters most commonly measured.

Staging of sleep is reasonably standardized, because most laboratories use the Rechtschaffen and Kales scoring system. Unfortunately, there is considerable variation in the definition of respiratory events, especially hypopneas. Similarly, the definition of what constitutes an arousal is inconsistent from laboratory to laboratory. Scoring of sleep apnea is predominantly based on the apnea-hypopnea index (AHI), which measures the average number of sleep-disordered breathing events per hour. Up to 5 events per hour are considered to be normal, whereas more than 30 events per hour are generally classified as severe, though that classification is also variable.

Multiple sleep latency testing (MSLT) is the most commonly used objective test to quantify daytime sleepiness. Typically performed on the day following PSG, it consists of a total of four or five monitored 20-minute naps at 2-hour intervals, with sleep latency defined as the interval between "lights-out" and the first 30 seconds of scorable sleep, and rapid eye movement (REM) latency as the interval from the beginning of the first epoch scored as sleep to the first epoch of REM sleep. Normal sleep latency is greater than 10 minutes, whereas less than 5 minutes is considered pathologic sleepiness. Normally, REM sleep is not seen during any trial; two or more episodes of sleep-onset REM suggest the diagnosis of narcolepsy.

While MSLT measures the tendency to fall asleep, maintenance of wakefulness testing (MWT) measures the ability to stay awake. The two propensities tend to be inversely correlated, and yet they are distinct, with some subjects showing disparate results on the same day. MWT is performed with the individual instructed to try to stay awake while sitting in a darkened, quiet room. The test consists of four 20- or 40-minute trials performed at 2-hour intervals. Normal latency is 18 minutes, with a lower limit of 11 minutes. MWT is assumed to be more occupationally relevant than MSLT, because it more nearly addresses the issue of concern in the occupational setting. It should be noted, however, that the MWT was validated in subjects who did not have a particular interest in the outcome.

ASTHMA

Asthma is an inflammatory disease of airways in response to various stimuli characterized by paroxysmal or persistent symptoms, such as dyspnea, chest tightness, wheezing, sputum production and cough associated with airway hyperresponsiveness, and variable airflow limitation. The prevalence of asthma is increasing in the industrialized world. The overall prevalence of lifetime asthma in the United States is 11.9% (4). The severity of asthma has also increased, with the death rate due to asthma doubling in the period 1980 to 1999 (5). Asthma is most common in childhood. Remission of childhood asthma may occur, with up to 25% remaining free of symptoms from adolescence onward. Most adult asthmatics have a history of childhood asthma, and positive markers of airway inflammation may be present in the absence of clinical symptoms or pulmonary function abnormalities.

The aeromedical concerns with respect to asthma include the potential for sudden incapacitation with acute attacks (e.g., with a cockpit smoke situation), small airways dysfunction causing $\dot{V}/\dot{Q}$ mismatching thereby magnifying hypoxia, acceleration atelectasis and lowered G tolerance, the potential for pulmonary barotrauma with acute decompression, and adverse effects of medications. In the operational military environment, constraints on wearing protective equipment and deployability issues are also concerns.

Asthma represents a spectrum of disease severity and the challenge for the flight surgeon/aeromedical practitioner is to quantify disease severity and to generate an appropriate aeromedical disposition based on an evidence-based risk assessment. The assessment should include detailed history, physical examination, and a pulmonary function assessment.

Evaluation of Asthma in Aircrew

History

Important in the history are careful documentation of the severity of past episodes including requirement for urgent medical care and/or hospitalization, particularly in the last several years. The medications required for acute episodes and for maintenance therapy reflect the disease severity. The use of short-acting β agonists (SABAs) more than three times a week other than for physical activity indicates inadequate control of asthma. The best predictor of severe asthmatic attacks is a history of such episodes.

Although asthma may arise *de novo* in adults, most adults with asthma have a history of childhood symptoms of asthma or recurrent bronchitis. Asthmatic children whose asthma remits permanently will almost all be free of symptoms by adolescence. The persistence of asthmatic symptoms into adolescence is of prognostic significance for adult asthma. Asthma symptoms may remit for a period of years, only to return.

Identification of trigger factors is important by providing potential options for nonpharmacologic intervention. These may include environmental allergens including animal dander (cats in particular), dust mites (e.g., in feather pillows and bedding), and pollens such as ragweed. Other common triggers include intercurrent viral infections, occupational triggers, exercise, and cold air. Up to 20% of asthmatics may exhibit aspirin sensitivity. Cigarette smoke is a nonspecific bronchial irritant which can complicate all types of asthma. Asthmatics may demonstrate exercise-induced bronchospasm (EIB), which is of particular concern in fast jet aircrew where strenuous exertion with anti-G straining maneuvers combined with PPB may induce bronchospasm.

Asthmatic episodes may occur in several patterns after exposure to allergens. The immediate response typically occurs within a few minutes of exposure and lasts 30 to 60 minutes, similar to the response after methacholine or exercise. Early responses may be prevented with sodium cromoglycate and generally respond well to inhaled short acting bronchodilators. Late asthmatic responses occur 6 to 8 hours after the inhaled challenge, are typically more severe, and resolve more slowly over 12 to 24 hours. Late reactions respond much more poorly to inhaled bronchodilators. Documentation of delayed or late asthmatic responses is of aeromedical significance. Nocturnal asthma (awakening at night with asthmatic symptoms) usually signifies heightened disease activity.

Careful documentation of the history from childhood onward provides crucial information for appropriate aeromedical disposition. In the case of candidates for aircrew training or licensure, minimizing past symptoms is common and historical information should be corroborated with additional data, for example, from family physicians.

Pulmonary Function Assessment

Pulmonary function testing provides objective data on lung function and airway reactivity. Unfortunately, there is no test specific for asthma, and during clinical remission asthmatics may have normal or near-normal pulmonary function. Assessment should include inspiratory and expiratory flows, lung volumes, airway resistance, and BPT. In individuals with histories suggesting exercise-induced asthma, exercise testing with airflow assessment before and after exercise may be helpful.

Flow-volume loops will generally show evidence of expiratory airflow limitation, although as mentioned, during clinical remission, some asthmatics may not have airflow limitation. Occasionally, inspiratory airflow limitation may be discovered as a manifestation of tracheomalacia.

Lung volume assessment may show evidence of gas trapping with increased residual volume, functional residual capacity (FRC) and/or total lung volume (see Chapter 2). Body plethysmographic lung volumes greater than helium dilution also suggest gas trapping, reflected in an FRC measured by the body box as 10% greater than the FRC measured by helium dilution.

FVC maneuver and lung volumes should be repeated after administration of a bronchodilator. An increase in flow rates suggests increased bronchomotor tone, and a significant decrease in lung volumes is an indicator of gas trapping. A 12% increase in FEV_1 (at least 180 mL) from baseline 15 minutes after inhalation of a β agonist is considered significant and an indication of asthma. BPT provides objective information about airway reactivity and should be performed as part of the aeromedical assessment of aircrew being evaluated for asthma. However, the prevalence of bronchial hyperreactivity far exceeds that of clinically manifest asthma, and some persons with hyperreactive airways do not have asthma. Additionally, a negative BPT, while indicating a clinical remission, does not predict long-term resolution of asthma. The results of BPT should be integrated with the clinical picture.

Even during clinical remission, asthmatics may have ongoing airway inflammation. Individuals whose asthma is triggered by inhaled allergens usually have atopic disease. Atopic individuals may show peripheral blood eosinophilia, increased immunoglobulin E (IgE) levels, and positive wheal-and-flare reactions to intradermal testing. Markers of airway inflammation include sputum eosinophils and increased levels of exhaled nitric oxide (eNO). eNO assessment is a noninvasive test that is a measure of airway inflammation. When available, elevated eNO levels documented with standardized testing reflect ongoing airway inflammation, even in the absence of clinical symptoms or pulmonary function test (PFT) abnormalities. Such testing may provide additional corroborative information in assessing aircrew for asthma.

In individuals with a history suggestive of EIB, an exercise test with flow-volume curves before and after a maximum exercise stress test may be helpful. A fall in FEV_1 greater than 12% within the first 30 minutes of exercise is considered significant.

Treatment of Asthma in Aircrew

Treatment of asthma in aircrew should follow established clinical guidelines (see Recommended Readings). Treatment considerations in aircrew should include avoidance of environmental allergens. Immunotherapy is generally not recommended in the treatment of asthma. Smoking cessation is an important therapeutic intervention and should be considered a requirement for continued aircrew duties.

SABAs are used for short-term control but may cause significant adrenergic side effects, and are not recommended before flight duties. Except for preexercise prophylaxis in aircrew with EIB, the requirement for SABAs on more than a very infrequent basis (e.g., in association with an intercurrent respiratory infection) suggests inadequate asthma control. Inhaled corticosteroids (ICS) attack the primary inflammatory mechanism of the asthmatic response, and should be considered early in the control of asthma for aircrew. The goal is to obtain full remission with inhaled steroids and to taper the dose to that required to maintain full control as assessed by history, self-monitored peak flow rates, and by repeat pulmonary function testing including normal bronchial provocation assessment. ICS are safe from an aeromedical perspective, and do not require flying restrictions. For asthmatic aircrew in whom good control is not achieved with maximum recommended doses of inhaled steroids, additional treatment with a long-acting β agonist (LABA) and/or a leukotriene inhibitor may be considered. Asthma requiring further intervention such as oral steroids or methotrexate is not considered compatible with aircrew duties.

Aeromedical Disposition

Appropriate aeromedical disposition depends on an evidence-based risk assessment based on potential flight safety and operational impact, and a full assessment of the individual aircrew including all historical information integrated with results of the pulmonary function assessment.

Aircrew Candidates

Because of the considerable expense associated with aircrew training, and potential adverse effects of even mild degrees of airways dysfunction in the high-G environment, a history of asthma is generally considered disqualifying for military aircrew selection. However, because of the increased tendency to label as asthmatic those children with a mild degree of wheezing from an intercurrent viral infection, a careful history is important, including data obtained from the pediatrician or family physician. For candidates with a history of mild childhood asthma with no requirement for urgent care or hospitalization following puberty, a full pulmonary function assessment including bronchial challenge testing should be carried out. If available, a standardized eNO test may provide further objective information about airway inflammation. Candidates with no clinical history of asthma following puberty, and normal pulmonary function assessment including normal bronchial reactivity may be carefully considered for aircrew training.

Experienced Aircrew

Aeromedical disposition for experienced aircrew with asthmatic symptoms will depend on their aircrew duties or type of license, results of the assessment as outlined, and medications used for control of their symptoms. Generally, because of the possibility of persistent small airways dysfunction even in the absence of symptoms, asthma is generally disqualifying for fast jet aircrew. Non–fast jet military or civilian aircrew, whose asthmatic symptoms are mild and are well controlled with inhaled steroids alone, and who have normal or near normal pulmonary function assessment including bronchial reactivity may be fit for continued aircrew duties. A normal eNO assessment also reflects good control of asthmatic inflammation. Such aircrew are unlikely to have an acute episode, even if medication is unavailable for several weeks. Additional requirement for a LABA or leukotriene inhibitor suggests a more severe degree of asthma, but may be compatible with some aircrew duties. In such individuals, there is an increased risk of developing increasing asthmatic symptoms in a shorter period without medications. Apart from preexercise prophylaxis, and the occasional exacerbation related to a viral infection, the use of SABAs is generally a reflection of poorly controlled asthma and is disqualifying for aircrew duties.

CHRONIC OBSTRUCTIVE PULMONARY DISEASE

COPDs occur less commonly in aircrew than asthma, primarily because the time course for development of clinically significant COPD spans the normal aircrew career. The Global Initiative for Chronic Obstructive Lung Disease (GOLD) defines five stages of COPD (see Recommended Readings). Except in unusual circumstances, COPD in aircrew would be anticipated to be GOLD stage I (mild). Clinically manifest disease (GOLD stages II–IV) would be expected only in the latter years of a military or commercial flying career or in retirement. However, since the pathophysiologic processes that lead to COPD are active during the flying years, aeromedical physicians are in an ideal position for primary prevention interventions, which may ameliorate these processes and prevent the development of COPD.

The primary underlying cause for COPD is cigarette smoking. Pipe, cigar, and exposure to passive smoke may likewise cause COPD. Other less common causes include exposure to dusts and chemicals. The global burden of COPD is significant with a prevalence estimated at one in ten adults older than 40 (6). COPD is now the fourth leading cause of death in the United States, and is projected to be the third leading cause by 2020 (7).

COPD includes chronic bronchitis and emphysema, two manifestations of permanent, largely irreversible airflow obstruction. Although clinically disparate, in practice the two disease processes often overlap. Chronic bronchitis is characterized by airway inflammation with enlargement of mucous glands, hypersecretion of mucus and structural changes in the bronchi. These findings are manifested by cough productive of sputum, and clinically chronic bronchitis is defined by the presence of a cough with sputum on most days for at least 3 months per year, for 2 or more years in succession. Emphysema is a destructive process involving the lung parenchyma in the distal airspaces, with enzymatic destruction of lung elastic and connective tissue resulting in the formation of emphysematous spaces.

Both processes cause increasingly severe disturbances of ventilation and perfusion distribution and matching, eventually resulting in hypoxia in even a one-atmosphere environment. In symptomatic stages, both diseases result in undue shortness of breath, at first during exertion, but later during even normal daily activities such as walking. Particularly with emphysema, these later symptomatic stages are preceded by an asymptomatic period, which in most individuals spans several decades, including a flying career in the case of aircrew.

The dominant feature of both chronic bronchitis and emphysema is an acceleration of the progressive decline in maximum achievable airflow that normally occurs with age. Cigarette smoking causes inflammatory changes in small airways, with mild bronchiolitis being an almost universal finding in even young smokers, whose lungs also show macrophage clusters around respiratory bronchioles and foci of peribronchiolar fibrosis. As these inflammatory and destructive changes progress with ongoing exposure to cigarette smoke, increasing airflow obstruction results.

The presence of increased numbers of macrophages around respiratory bronchioles in even young smokers is thought to be related to the processes, which result in emphysema. Macrophages secrete proteases, activated oxygen radicals, and neutrophil chemotactic factors, the result of which is to initiate tissue-destructive processes.

The lungs are normally afforded protection from the tissue destructive action of elastases and other proteases by protease inhibitors such as α-1 protease inhibitor (also called *α-1 antitrypsin*), which conjugates with and inactivates the proteases. Deficiency of α-1 antitrypsin is an autosomal recessive inherited disease, which results in the early development of emphysema in patients homozygous for a particular α-1 antitrypsin allele termed *PiZZ*. The incidence of this disorder is approximately 1:3,000 in the population. Homozygous PiZZ individuals have serum concentrations of α-1 anti-trypsin only 10% to 15% of normal. Emphysema develops in more than 80% of such individuals even in the absence of smoking, with a distribution of bullae which includes lung bases. Symptoms generally develop in the 45 to 50 age range, but earlier in smokers. These individuals may also show liver function abnormalities. Heterozygous individuals (PiMZ) generally have α-1 antitrypsin levels approximately 50% of normal. Such individuals may also be predisposed to a greater deterioration in lung function than normal, especially if smokers.

Fortunately, there is good evidence that early intervention by smoking cessation will prevent the acceleration of airflow limitation characteristic of COPD. This is most effective in the early phases, and becomes less effective as an intervention in later stages of COPD.

Smokers including aircrew are generally quick to point out that not all smokers go on to develop COPD, and most smokers count on being among those who do not. Routine periodic pulmonary function screening can help identify those smokers who are headed for trouble from COPD, and should form part of the periodic assessment of all aircrew who smoke. Early evidence of small airways dysfunction and airflow limitation provides evidence of early airway obstruction, important information for flight surgeons in discussing smoking-cessation interventions with aircrew. Conversely, if an asymptomatic smoker has a normal FEV_1 at age 40, it is unlikely that such an individual will develop symptomatic COPD. Nonetheless, other smoking-related risks including lung cancer and atherosclerotic (particularly coronary) disease remain critical issues.

As lung tissue destruction progresses from the emphysematous process, pulmonary function changes occur with a decrease in diffusing capacity (DLCO), and evidence of lung hyperinflation and gas trapping.

Aeromedical Concerns

Of significant aeromedical concern, even during the presymptomatic period, the disturbances of ventilation and perfusion (which develop as part of the pathophysiologic disease process) may result in significant hypoxia occurring in what might otherwise be a mildly hypoxic hypobaric environment, for example at cabin altitudes of 8,000 to 10,000 ft (2,438–3,048 m). Such altitudes generally do not result in significant hypoxia in normal individuals, but in those with even mild to moderate COPD, $\dot{V}/\dot{Q}$ mismatch may result in arterial oxygen tensions in the steep portion of the oxyhemoglobin dissociation curve, where even small decreases in arterial oxygen tension may result in significant drops in oxygen saturation. This risk is intensified by exercise; even modest degrees of exercise at mildly reduced oxygen saturations on the steep portion of the oxyhemoglobin dissociation curve may result in significant desaturation and hypoxic symptoms.

Small airways dysfunction may predispose to small airway closure in a high-G environment, resulting in acceleration atelectasis, and possible compromise of G tolerance. These problems may be magnified with new generation enhanced G-protective equipment, with fluxes of intrathoracic blood volume further compromising small airway function. With increasing G forces and onset rates in new high-agility fighter aircraft, tissue destruction by the emphysematous process may increase the risk of parenchymal damage in the lung, which has been termed the *Achilles' heel* of man in the high-G environment (1). The addition of positive pressure for both high-altitude hypoxia and G protection further increases concerns about damage to lungs weakened by a presymptomatic emphysematous process.

Finally, in individuals with more advanced COPD with gas trapping and bullous transformation, pulmonary barotrauma becomes a risk especially with acute decompression, which may occur either through loss of cabin pressure, or during aeromedical training with altitude chamber exposures.

Aeromedical Evaluation and Disposition

Aircrew Candidates

Screening PFTs should be included in the assessment of candidates for military pilot training. At a minimum, testing should include an FVC maneuver, preferably assessed as a flow-volume loop. Candidates who show evidence of airflow limitation or reduced volume should undergo further assessment with full pulmonary function testing including lung volumes and diffusing capacity. Candidates with a family history of COPD, especially of early-onset emphysema, should be assessed for α-1 antitrypsin deficiency. With the vast improvement in therapy in recent years, the possibility of cystic fibrosis should also be considered in candidates with abnormal baseline spirometry. Individuals with fixed airflow limitation, especially if smokers, are not good candidates for aircrew training.

Experienced Aircrew

Pulmonary function testing should be part of the aeromedical assessment of all aircrew who smoke. At a minimum, this should include an FVC with measurement of FEV_1 and FVC, but for enhanced sensitivity for early small airway dysfunction, testing should include measurement of forced expiratory flow rates at 50% vital capacity (FEF_{50}), and volume-time derived mid-maximal flow rate ($MMFR_{25-75}$) as well as lung volumes and measurement of diffusing capacity (DLCO).

Aircrew who smoke, especially those who show early evidence of pulmonary dysfunction, should be strongly encouraged toward smoking cessation. The importance of early smoking cessation in reversing lung damage caused by smoking should be emphasized, along with the danger of ignoring the relatively long asymptomatic period before established COPD becomes symptomatic, at which time reversibility is limited and career implications a certain reality. Current intervention modalities have improved outcome results with respect to smoking cessation, including smoking cessation groups, nicotine gum, transdermal nicotine patches, and medications such as bupropion or varenicline. Temporary grounding or a flying restriction may be required during intervention with the last modalities. Repeated encouragement by health care providers including flight surgeons has been demonstrated to be one of the most effective strategies in successful smoking cessation. The importance of the aeromedical practitioner in this important primary prevention role cannot be overemphasized.

For aircrew who demonstrate small airways dysfunction on pulmonary function testing, and especially with any evidence of a decrease in diffusing capacity, measurement of α-1 antitrypsin levels should be performed, and reduced levels followed up by genotyping as indicated.

Uncommonly, flight surgeons may encounter aircrew with manifest COPD resulting from α-1 antitrypsin deficiency, from smoking beginning at an early age, or rarely from lung damage from smoke inhalation. For aircrew with established COPD, the aeromedical assessment should include full pulmonary function assessment including exercise testing to assess exercise capacity, lung imaging with CT scan to assess for bullae, and assessment of oxygen saturation and/or blood gases with exposure to altitude or a hypoxic gas mixture, such as the reduced oxygen breathing device (ROBD), or combined altitude and depleted oxygen system (CADO).

Aircrew with even early COPD on pulmonary function testing are unlikely to be suitable for fast jet operations, especially in the latest generation hyperagile fighter aircraft with enhanced G-protection ensembles. With the development of fixed airflow limitation, gas trapping, and a decrease in diffusing capacity, permanent grounding may be required especially if desaturation occurs with exercise or during exposure to altitudes below 10,000 ft (3,048 m). Medical certification of civilian aircrew with COPD should include assessment of the potential for significant hypoxia at operational cabin or unpressurized flying altitudes using hypoxic gas mixtures or chamber altitude exposures.

Assessment of passengers with COPD for air travel is discussed in Chapter 26. Increasing interest in commercial space travel may result in clients with COPD seeking commercial space flights (see Chapter 30). The physiologic challenges associated with such flights require in-depth aerospace medical assessments (8).

CYSTS AND BULLAE

Coalescence of emphysematous sacs may lead to the development of larger airspaces; those exceeding 1 cm in diameter are called *bullae*. Pulmonary bullae most commonly develop at the apices of the lungs, reflecting the regional gravitational shearing stresses on the lung of the normal 1-G environment. Apical bullae may be adjacent to the visceral pleura, forming the substrate for a pneumothorax should rupture occur. [These should not be confused with subpleural blebs, which are the usual cause of primary spontaneous pneumothorax (PSP), and typically occur in the absence of any parenchymal bullous changes.] Adjacent bullae can merge into very large bullae, which may occupy up to a third of a lung and cause symptoms by compressing normal lung tissue. Cysts are enlarged spaces, occasionally air-filled, which may be congenital (e.g., bronchogenic cysts), or develop from a variety of causes, including cavitary infections (e.g., tuberculosis, histoplasmosis, or coccidiomycosis).

Under normal circumstances at ground level, cysts and bullae generally behave as space-occupying lesions, and do not significantly affect gas exchange because both tidal ventilation and blood flow in such areas are minimal. Extremely large bullae may interfere with gas exchange by compressing adjacent lung tissue resulting in atelectasis.

The primary aeromedical concerns with respect to pulmonary blebs and bullae are first, the risk of rupture during decompression resulting in pneumothorax, mediastinal emphysema, or as an unlikely but catastrophic possibility, arterial gas embolism, and second, for large cysts and bullae, the risk of expansion with altitude decompression, resulting in compression of the remaining normal lung. A further hypothetical concern in aircrew flying fast jet or aerobatic aircraft relates to the possible risk of accelerating expansion of the bulla over time with repeated exposure to the increased shear stresses of radial accelerative forces. The potential risk for rupture in the high-G environment is compounded by added distortion of the lung with +Gz, with potential added stress from PPB.

Whether or not cysts and bullae expand with altitude decompression, with concomitant risk of enlargement with lung compression and/or rupture during flight, depends largely on the degree of patent airway communication of the cyst/bulla with major airways. This may be assessed in several ways (1): difference in lung volumes obtained by gas-equilibration methods, for example, helium dilution compared with body plethysmography, because poorly communicating airspaces will not equilibrate during helium dilution, with resultant smaller measured lung volumes compared with plethysmography (2); absence of ventilation on a ^{133}Xenon (^{133}xe) lung scan (3); the absence of change in size on a full expiratory compared with full inspiratory chest x-ray; or (4) if facilities are available, the demonstration of expansion in size on chest x-ray during altitude chamber exposure. However, it should be noted that arterial gas embolism during chamber training has been described with cavities as small as 4 cm. Rupture of pulmonary bullae causing hemoptysis and even death has been anecdotally reported in passengers.

Pulmonary cysts and bullae are generally asymptomatic unless very large, and are generally discovered on chest x-ray carried out for other reasons. Further assessment should include high-resolution CT scan of both lungs, and assessment of degree of communication with airways as mentioned earlier.

The aeromedical disposition depends on the result of the assessment, taking into consideration the aircrew's flying role. For non–fast jet aircrew, small cysts or bullae may be compatible with unrestricted duties without intervention; annual surveillance with chest x-ray or CT scan is required. For larger, poorly communicating bullae in military aircrew, resection is recommended. For fast jet aircrew, resection of bullae with pleurodesis is recommended for continuing aircrew duties. Following adequate resection and pleurodesis, and a convalescent period of at least 3 months to allow for adequate healing, assessment with pulmonary function testing, pressure breathing, and altitude chamber testing is recommended before returning to flight duties. Bullous disease which develops as a complication of significant COPD/emphysema is incompatible with flying duties.

SPONTANEOUS PNEUMOTHORAX

Spontaneous pneumothorax (SP), perhaps best defined as air in the pleural space of nontraumatic cause, is usually divided into primary and secondary forms. Secondary SP, which occurs in the presence of underlying parenchymal or airway disease, is usually a disease of older individuals, and its management is heavily influenced by the underlying lung disease. Primary spontaneous pneumothorax (PSP), on the other hand, is a disease predominantly of younger males, peaking in the second and third decades of life, with a significant rate of recurrence and obvious aeromedical implications.

The incidence of PSP is estimated to range from 7.4 to 37/100,000/yr among men, and 1.2 to 15.4/100,000/yr among women. The true rate is likely higher; in large series, 1% to 2% of cases were usually discovered incidentally. The vast majority of individuals are found to have subpleural blebs at the time of thoracoscopy or surgery. Taller, thinner individuals seem to be at particular risk for developing such blebs (9).

Although most SPs in women arise from the same etiology, any female patient with SP should be questioned about her menstrual history. An episode occurring within 48 to 72 hours of the onset of menses is suspicious for catamenial pneumothorax, and recurrent pneumothoraces associated with menses should be considered diagnostic. The underlying etiology is confusing, because pleural endometrial implants have been implicated in some patients, and diaphragmatic fenestrations in others. The distinction from the usual form of SP is important, because suppression of ovulation by oral contraceptive steroids may be sufficient to prevent recurrence of the catamenial form.

Judging from most series, the onset of PSP appears to be random, with no particular predilection for periods of activity. There does appear to be an increased risk of precipitation under hypobaric conditions; a review of 112 aviators with PSP showed that 11% of these episodes occurred during flight, and another 6% occurred in the altitude chamber, nearly all of the latter developing immediately after a rapid decompression maneuver (10). Virtually all symptomatic patients with SP experience ipsilateral pleuritic chest pain. Approximately two thirds of PSP patients also describe dyspnea. With the exception of tachycardia, physical findings are usually absent unless the pneumothorax is quite large, at which point increased resonance and diminished breath sounds may be appreciated. The *conditio sine qua non* for diagnosis of a pneumothorax is the finding of a visceral pleural line, best visualized in the apex on a standard chest radiograph.

Several medical issues arise with SP. The pleuritic pain associated with SP can be severe, and even incapacitating. Barometric pressure changes associated with aviation will affect the size of a pneumothorax, causing expansion and greater respiratory compromise with ascent, and compression of the pneumothorax with descent.

The immediate treatment of a PSP is determined partly by its size. A small pneumothorax (usually $<15\%$) with minimal symptoms may be treated by observation; the pleura can reabsorb air at a rate of 1% to 2% of the hemithoracic volume per day, a rate that is at least quadrupled by the use of supplemental oxygen. Larger pneumothoraces may be treated by simple aspiration, which is sufficient in approximately two thirds of cases. Finally, a chest tube may be inserted and removed after the air leak stops. Compared to a standard chest tube, a small-bore catheter attached to a one-way valve results in less discomfort, better mobility, and shorter hospitalizations, and is usually quite adequate for PSP.

The most significant aeromedical concern centers on the risk of recurrence. The risk of another pneumothorax is approximately 30% after a first episode, 60% after a second episode, and 80% after a third. Approximately 10% of recurrences are contralateral. Roughly two thirds of recurrences take place within the first 2 years, although this proportion is subject to wide variation in the literature. There is considerable controversy about when to intervene to prevent recurrence. Historically, clinical patients experiencing a second pneumothorax have been treated surgically to prevent further recurrence, but there is sound aeromedical argument for surgical prophylaxis even after the first episode in an aviator. An attractive alternative would be to identify and treat those at higher risk of recurrence, which might be achieved by determining the presence of blebs on high resolution CT. Unfortunately, studies evaluating the utility of this method have been small and contradictory (11,12).

Procedures to prevent recurrence of pneumothorax primarily consist of scarification, either by chemical or mechanical means, or resection of the pleura. Chemical pleurodesis has been attempted with a variety of sclerosing agents, most commonly tetracycline and talc. Parenteral tetracycline is no longer available, and while other related drugs are probably equivalent, the recurrence rate of 10% to 25% seen with such treatment is unacceptable for aeromedical purposes. Talc is more efficacious, with success rates approaching that achieved by abrasive pleurodesis or pleurectomy, but concerns about its use persist. Talc has been associated with acute respiratory distress syndrome; this had been thought to be limited to administration as a slurry, but more recently insufflated talc, or poudrage, has also been implicated. Furthermore, the use of intrapleural talc occasionally results in significant pleural fibrosis in later years. Mechanical abrasive pleurodesis using thoracoscopy results in recurrence rates of 0% to 6%, similar to those achieved with open pleurodesis. Pleurectomy, whether by thoracoscopy or thoracotomy, is equally successful, but is technically more involved and offers no further advantages.

INTERSTITIAL LUNG DISEASES

A diverse group of disorders, interstitial lung diseases (ILD) are usually considered together because of similar symptoms and radiographic findings. The typical patient presents with dyspnea on exertion, diffuse interstitial infiltrates on chest film, and a restrictive pattern on pulmonary function testing. On occasion, however, an asymptomatic patient may be discovered to have an interstitial pattern on x-ray, with or without restriction on PFTs; the dilemma in this situation is to determine whether this represents damage from an old insult, such as viral pneumonia, or an early stage of progressive disease. Interstitial diseases may be acute or chronic. It is most useful to divide ILD into those of known etiology, such as infections (e.g., viral, fungal), environmental exposures (e.g., silica, asbestos), or drug reaction, and those of unknown etiology.

The primary aeromedical concerns with most forms of interstitial lung disease center on functional impairment and disease stability. Functional impairment is most likely to be due to dyspnea and/or hypoxemia. Dyspnea is a distressing symptom, which, in the absence of progression of ILD, tends to be relatively consistent for a given level of exertion. Hypoxemia is largely due to $\dot{V}/\dot{Q}$ mismatching, although diffusion limitation may also play a role when cardiac output increases. In early stages of chronic ILD, resting arterial oxygen saturation is usually normal, although desaturation with exercise is common. As the disease progresses, $\dot{V}/\dot{Q}$ mismatching and eventually shunting give rise to resting hypoxemia and hypocarbia. The degree of impairment of oxygenation should be judged not by the resting P_{O_2} but by the alveolar/arterial oxygen difference (AaD_{O_2}), which normally averages 7 mm Hg at age 20, and rises to 15 mm Hg at age 60. Aviators with stable disease, with dyspnea either absent or occurring only after strenuous exertion, and with a normal or minimally elevated AaD_{O_2} can be considered for return to general aviation. Those with progressive disease are by definition unstable, and commonly require intensive therapy with corticosteroids or other immunosuppressants, either of which would render return to aviation duties inadvisable.

SARCOIDOSIS

Although usually considered under the rubric of ILD, sarcoidosis is actually a systemic granulomatous disease which commonly involves the lungs, along with hilar and mediastinal nodes. It may also present with or be complicated by dermal, ocular, hepatic, cardiac, or neural involvement. Endocrine manifestations may include either true or pseudodiabetes insipidus, due to vasopressin deficiency or polydipsia (depending on whether the pituitary or hypothalamus is involved, respectively), and hypercalcemia, due to production of calcitriol in granulomata. Anatomic presence of disease in an organ without clinical evidence of dysfunction is a common feature of sarcoidosis; with the general exception of the brain and heart, where involvement is less likely to be silent, a considerable burden of disease may exist without seriously disrupting the function of an organ. Clinical cases of cardiac or neurologic sarcoid often appear to be confined to the respective organ system, suggesting that isolated subclinical disease is a more frequent occurrence than is generally appreciated.

Arising typically in the third or fourth decades of life, sarcoidosis is the interstitial pulmonary disease most likely to be encountered in aeromedical practice. Management of pulmonary sarcoidosis does not differ significantly from that outlined from ILD in general, except that sarcoidosis is prone to intermittent exacerbations and remissions. Although the need for biopsy confirmation of sarcoidosis is arguable in the clinical setting, the aeromedical issues surrounding sarcoidosis, and the alternative differential diagnoses such as lymphoma, are complex enough that a histologic diagnosis is advisable in the aviator.

It is the frequent occurrence of extrapulmonary disease that sets sarcoidosis apart from other ILD, and further complicates aeromedical management. In addition to the lung, the organ systems of greatest aeromedical interest that are most likely to be involved with sarcoidosis are the eye, brain, and heart.

Ocular sarcoidosis most often presents as inflammation of the uveal tract, classically as an anterior, usually granulomatous uveitis, although posterior chorioretinitis is also common. Conjunctival involvement is somewhat less common, and certainly less serious, but may serve as a useful site for biopsy to obtain histologic confirmation. The eye is reported to be involved in 25% to 50% of sarcoid patients, although this number probably reflects referral bias. A thorough ophthalmologic examination is required of any aviator with a diagnosis of sarcoidosis. Uveitis from sarcoid can be severe, occasionally even resulting in blindness as a direct consequence of inflammation or from secondary glaucoma. Acute uveitis requires treatment with topical corticosteroids, while more severe cases may require systemic steroid therapy. Active uveitis requires grounding until remission is achieved.

Clinical neurosarcoidosis is consistently reported to occur in 5% of sarcoid patients, and may involve virtually any part of the central or peripheral nervous system. Cranial nerve palsies, meningitis, and hypothalamic/neurohypophyseal dysfunction are classic presentations (13). Seizures have been reported in 5% to 22% of neurosarcoidosis cases, but only occasionally at presentation (14). Abnormal mental status has also been rare as the presenting manifestation. The aviator with a new diagnosis of sarcoidosis in another organ should receive a thorough neurologic examination; in the absence of any signs or symptoms of neural involvement, further workup is probably not indicated.

The greatest aeromedical concern is undoubtedly cardiac sarcoidosis. Reports from autopsies have documented myocardial involvement in 20% to 50% of subjects, but the bias of these series is evident; compared with the involvement of other organs by sarcoidosis, involvement of the myocardium is much more likely to be fatal. Unfortunately, sudden death is not uncommon as the presenting manifestation. The best available clinical estimates are that 5% of sarcoid patients have clinical cardiac involvement. Sarcoid granulomata tend to favor the basal portion of the interventricular septum and the left ventricular free wall; right ventricular involvement is less common and atrial involvement even less so. Typical clinical presentations include conduction defects, such as complete heart block or intraventricular conduction delay, ventricular arrhythmias, congestive heart failure, and sudden death (15).

The primary aeromedical question centers on the extent of workup advisable to detect cardiac disease in an aviator who is found to have sarcoidosis in another organ system. Several noninvasive modalities have been touted as useful for detecting cardiac involvement, but most authors seem to ignore the possibility of false-positive studies in the normal heart. Furthermore, all suffer from the lack of a reference standard; endomyocardial biopsy has a high miss rate, due to the uneven distribution of granulomata and because the biopsy site is commonly in the apical septum, whereas the granulomata tend to be basal in distribution. Recently, magnetic resonance imaging (MRI) has been suggested as the optimum method of detecting cardiac involvement, but in a recent study the positive predictive value of an abnormal MRI was only 55%, using a clinical diagnosis of cardiac involvement as the reference standard (16). To screen an aviator with sarcoidosis for cardiac involvement, it seems most reasonable to obtain ambulatory electrocardiographic monitoring to evaluate for conduction block, ventricular arrhythmias, and frequent premature ventricular complexes (>100 per day or 1% of total complexes). The primary aeromedical concern is rhythm disturbance, and such findings have been shown to correlate reasonably well with known disease (17). Exercise testing may also demonstrate arrhythmias due to myocardial sarcoid involvement, although there is a risk of having to additionally evaluate any findings suggestive of ischemia. Should ambulatory monitoring be abnormal, further cardiac testing including imaging studies would then be indicated. Such an approach addresses the greatest aeromedical concern, that is, rhythm disturbance, and increases the pretest probability that an abnormality on an imaging study represents a true positive.

CLINICAL SLEEP DISORDERS

Narcolepsy

Because of the prevalence of sleep apnea, sleep disorders are commonly managed by pulmonary specialists. However, narcolepsy, the second most common cause of pathologic hypersomnolence, is clearly a neurologic disorder. Population prevalence is lower than sleep apnea, averaging 0.05%, and shows a strong genetic component (18). The peak age of onset is 15 years, but onset in the third or fourth decade is also common. The cardinal symptom, hypersomnia, may precede the appearance of associated symptoms by months or years.

Excessive daytime sleepiness typically manifests as unanticipated naps, often lasting only seconds or minutes. As is true of sleep apnea, these episodes most often occur under conditions of reduced stimulation, but unlike sleep apnea, the naps are usually refreshing. Ancillary symptoms typical of narcolepsy include cataplexy, a sudden loss of muscle tone nearly always precipitated by emotion. Occurring in approximately 60% to 70% of narcoleptics, cataplexy is typified by paralysis lasting up to 2 minutes, with unimpaired consciousness. Although complete postural collapse is the classic presentation, cataplexy may be subtle; for example, laughter may be followed by transient weakness involving the neck muscles, with difficulty holding the head up. Sleep paralysis, seen in 60% of narcoleptics, usually occurs while falling asleep or awakening, and consists of near total paralysis lasting seconds to minutes; as in REM sleep, eye motility and respiration are spared. Hypnagogic (sleep onset) and hypnopompic (awakening) hallucinations are experienced by roughly a quarter of narcoleptics. Automatic behavior, sometimes bizarre, may occur in up to 80% of patients. Automatic behavior can be a feature of severe sleepiness due to other etiologies, but it appears more commonly in narcolepsy, where it may be due to rapidly oscillating states of wakefulness and sleep. All the manifestations of narcolepsy seem to result from impaired control of the boundaries separating wakefulness from sleep, especially REM sleep. Cataplexy and sleep paralysis represent intrusion of REM atonia, while the hallucinations represent dreams intruding into the waking state. It is important to note that many normal individuals, especially when sleep deprived, will occasionally experience similar sleep-onset and sleep-offset phenomena (i.e., sleep paralysis or hallucinations); in contrast, cataplexy is not seen in normal individuals, and classic cataplexy is almost diagnostic for narcolepsy.

Diagnosis is based on formal sleep studies, and is most commonly made from MSLT. It is critical that MSLT be properly performed to avoid a false-positive test, because narcolepsy is incompatible with aviation; pharmacotherapy with stimulants is frequently beneficial, but the effect is rarely more than partial.

Sleep Apnea

OSA, consisting of recurrent episodes of cessation (apnea) or reduction (hypopnea) of ventilation during sleep, is roughly 100-fold more common than narcolepsy, and is far less likely to have declared itself before flying training. While the prevalence varies depending on the definition, the accepted prevalence in the United States is that OSA affects 4% of men and 2% of women between the ages of 30 and 60. OSA was defined in that study as an AHI of greater than 5 events per hour, associated with daytime hypersomnolence (19).

OSA is best viewed along a continuum of sleep-disordered breathing. With deeper stages of sleep muscle tone is generally reduced, and while the diaphragm is spared the pharyngeal muscles are not. The negative intraluminal pressure during inspiration causes narrowing of the upper airway and, in increasing order of severity, this may result in vibration, significantly negative inspiratory pressures, or reduction/cessation of airflow. Vibration of the airway, or snoring, is usually considered a social rather than a medical issue. Its prevalence certainly argues for calling it a normal variant; the study noted earlier found 44% of men and 28% of women to be habitual snorers (19). Whether heavy snorers are at risk for complications in the absence of arousals or airflow reduction is unclear. Significantly negative inspiratory pressures result in increased respiratory effort, which may be severe enough to disrupt sleep even in the absence of reduced airflow. Such effort-related sleep disruption combined with diurnal hypersomnolence had been termed *upper airway resistance syndrome* but is now included within the definition of OSA. Greater degrees of obstruction result in reduction or cessation of airflow despite continued inspiratory effort, which typically leads to multiple arousals from sleep. Although arousal results in reestablishment of airway tone and patency, the quality of sleep and the percentage of time spent in deep sleep are affected. Prolonged apneas or hypopneas also frequently result in nocturnal hypoxemia. In addition, sleep apnea is associated with an increased risk of hypertension and myocardial infarction.

Obesity is the commonest risk factor for OSA, and because obesity is less common in aviators than in the general population, the prevalence of OSA in flyers is probably lower than the 2% to 4% noted earlier, though the true prevalence is unknown. OSA is of major concern to aviation medicine, because of the risk of daytime hypersomnolence and of cognitive dysfunction which may result from prolonged sleep deprivation and/or recurrent hypoxemia. Whether qualitative or quantitative in nature, sleep deprivation is a cumulative problem. Restriction of sleep to 6 hours or less per night for 14 nights was shown to be equivalent on the basis of cognitive performance deficits to 2 successive nights without sleep (20). It is worth noting that the subjects in this study were largely unaware of their increased cognitive deficits.

Aviation data is very scant, but it is clear that sleep apnea is a significant risk factor for automobile accidents, with crash rates showing a threefold to sevenfold increase in apneics compared with controls (21,22). Although falling asleep undoubtedly accounts for much of the increased risk, an absence of such a history provides little reassurance. Studies using driving simulation have shown impaired vigilance and increased tracking errors, in some cases even exceeding that seen in nonapneics impaired by alcohol (23,24). Such impairment has been shown to improve with treatment (25), and treatment has also been shown to reduce self-reported crashes by 50% to 75% (26). Because differences are easier to detect in those most severely affected, most studies have evaluated individuals with severe sleep apnea. However, there is evidence of cognitive dysfunction even in individuals with mild sleep apnea, which has also improved following treatment (27,28).

Under current clinical guidelines, an adult is considered to have OSA if the AHI is greater than 5 events per hour with associated symptoms, or 15 per hour without symptoms. Treatment recommendations have been published based on nasal continuous positive airway pressure (nCPAP) as standard therapy (29). Those guidelines recommend treatment for all individuals with an AHI equal to or greater than 30 events per hour, with treatment also recommended for individuals with an AHI between 5 and 30 events per hour when symptomatic. Because of the insidious onset of OSA, patients are often symptomatic but inclined to ascribe their fatigued state to a busy schedule, a misperception that is not corrected until treatment is instituted. Also, as noted earlier, impairment related to chronic sleep deprivation can be difficult for the patient to detect. Lastly, in occupational settings, personal motives may also come into play. Therefore, treatment is often recommended for any mission-critical worker (e.g., pilot, bus driver) with an AHI greater than 5 per hour.

The likelihood that symptoms will be absent in the aviator complicates treatment decisions, and objective methods to measure the effect of OSA would be helpful. The MWT is considered the standard method of measuring a subject's ability to stay awake. However, it was validated in populations where degree of motivation was not a particular issue. In USAF experience, although the longer modified MWT is employed, aviators with severe elevations of AHI have rarely fallen asleep during any 40-minute trial. Neurocognitive testing appears to be more sensitive at measuring impairment, but a standardized test battery has yet to be validated clinically.

Because the PSG is scored while asleep, motivation is not an issue, but consistency across laboratories is another matter. Scoring of respiratory events, particularly hypopneas, varies significantly and guidelines aimed at standardization have not been consistently implemented. The physician evaluating aviators for sleep apnea would be well advised to seek out an established laboratory and refer to that facility, at least until widely accepted standards are in place.

With reasonable compliance, nCPAP is an effective therapy, but for military applications it is incompatible with austere environments. Weight loss can be very effective in the obese apneic, with marked improvement often occurring after relatively minor (e.g., 20 lb) weight loss. Although achieving and especially maintaining weight reduction is always problematic, continued flying status can be a potent motivator. Positional therapy may also be tried, particularly when there is a marked difference in AHI between supine and nonsupine positions. Oral appliances which provide nonsurgical advancement of the mandible are frequently useful in mild to moderate apnea. Uvulopalatopharyngoplasty, although quite effective for snoring, significantly reduces apnea in only about half of patients. Maxillary-mandibular advancement is more effective, but also involves more extensive surgery.

REFERENCES

1. Wood EH, Hoffman EA. The lungs, "Achilles' heel" of air breathers in changing gravito-inertial environments. *Physiologist* 1984;27:47–48.
2. Crapo RO, Casaburi R, Coates AL, et al. Guidelines for methacholine and exercise challenge testing-1999. *Am J Respir Crit Care Med* 2000;161:309.
3. Taylor DR, Cowan JO, Greene JM, et al. Asthma in remission: can relapse in early adulthood be predicted at 18 years of age? *Chest* 2005;127:845–850.
4. Mannino DM, Homa DM, Akinbami LJ, et al. *Surveillance for asthma—United States 1980–1999. MMWR Morb Mort Wkly Rep* 2002;51:1.
5. Asthma prevalence and control characteristics by race/ethnicity—United States 2002. *MMWR Morb Mort Wkly Rep* 2004;53(7):145–148.
6. Halbert RJ, Natoli JL, Gano A, et al. Global burden of COPD: systematic review and meta-analysis. *Eur Respir J* 2006;28:523–532.
7. US National Institutes of Health. *COPD Fact Sheet. US National Institutes of Health Publication Number 03-5229*. http://www.nhlbi.nih.gov/health/public/lung/other/copd_fact.pdf. March 2003.
8. Jennings RT, Murphy DMF, Ware DL, et al. Medical qualification of a commercial spaceflight participant: not your average astronaut. *Aviat Space Environ Med* 2006;77:475–484.
9. Abolnik IZ, Lossos IS, Gillis D, et al. Primary spontaneous pneumothorax in men. *Am J Med Sci* 1993;305:297–303.
10. Voge VM, Anthracite R. Spontaneous pneumothorax in the USAF aircrew population: a retrospective review. *Aviat Space Environ Med* 1986;57:939–949.
11. Mitlehner W, Friedrich M, Dissmann W. Value of computer tomography in the detection of bullae and blebs in patients with primary spontaneous pneumothorax. *Respiration* 1992;59:221–227.
12. Sihoe ADL, Yim APC, Lee TW, et al. Can CT scanning be used to select patients with unilateral primary spontaneous pneumothorax for bilateral surgery? *Chest* 2000;118:380–383.
13. Scott TF. Neurosarcoidosis: progress and clinical aspects. *Neurology* 1993;43:8–12.
14. Delaney P. Neurologic manifestations in sarcoidosis—review of the literature, with a report of 23 cases. *Ann Int Med* 1977;87:336–345.
15. Sharma OP, Maheshwari A, Thaker K. Myocardial sarcoidosis. *Chest* 1993;103:253–258.
16. Smedema JP, Snoep G, van Kroonenburgh MP, et al. Evaluation of the accuracy of gadolinium-enhanced cardiovascular magnetic resonance in the diagnosis of cardiac sarcoidosis. *J Am Coll Cardiol* 2005;45:1683–1690.
17. Suzuki T, Kanda T, Kubota S, et al. Holter monitoring as a noninvasive indicator of cardiac involvement in sarcoidosis. *Chest* 1994;106:1021–1024.
18. Silber MH, Krahn LE, Olson EJ, et al. The epidemiology of narcolepsy in Olmsted County, Minnesota: a population-based study. *Sleep* 2002;25:197–202.
19. Young T, Palta M, Dempsey J, et al. The occurrence of sleep-disordered breathing among middle-aged adults. *N Engl J Med* 1993;328:1230–1235.
20. Van Dongen HP, Maislin G, Mullington JM, et al. The cumulative cost of additional wakefulness: dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep* 2003;26:117–126.
21. Baumel MJ, Maislin G, Pack AI. Population and occupational screening for obstructive sleep apnea: are we there yet? *Am J Respir Crit Care Med* 1997;155:9–14.
22. Terán-Santos J, Jiménez-Gómez A, Cordero-Guevara J. Cooperative Group Burgos-Santander. The association between sleep apnea and the risk of traffic accidents. *N Engl J Med* 1999;340:847–851.
23. George CFP, Boudreau AC, Smiley A. Simulated driving performance in patients with obstructive sleep apnea. *Am J Respir Crit Care Med* 1996;154:175–181.
24. Juniper M, Hack MA, George CF, et al. Steering simulation performance in patients with obstructive sleep apnoea and matched control subjects. *Eur Respir J* 2000;15:590–595.
25. Hack M, Davies RJO, Mullins R, et al. Randomised prospective parallel trial of therapeutic versus subtherapeutic nasal continuous positive airway pressure on simulated steering performance in patients with obstructive sleep apnea. *Thorax* 2000;55:224–231.
26. Sassani A, Findley LJ, Kryger M, et al. Reducing motor-vehicle collisions, costs, and fatalities by treating obstructive sleep apnea syndrome. *Sleep* 2004;27:453–458.
27. Redline S, Adams N, Strauss ME, et al. Improvement of mild sleep-disordered breathing with CPAP compared with conservative therapy. *Am J Respir Crit Care Med* 1998;157:858–865.
28. Engleman HM, Kingshott RN, Wraith PK, et al. Randomized placebo-controlled crossover trial of continuous positive airway pressure for mild sleep apnea/hypopnea syndrome. *Am J Respir Crit Care Med* 1999;159:461–467.
29. Loube DI, Gay PC, Strohl KP, et al. Indications for positive airway pressure treatment of adult obstructive sleep apnea patients—a consensus statement. *Chest* 1999;115:863–866.

RECOMMENDED READINGS

Becker A, Lemière C, Bérubé D, et al. Summary of Recommendations from the Canadian asthma consensus guidelines, 2003. *CMAJ* 2005;173(Suppl 6):S3–S11.

Caples SM, Gami AS, Somers VK. Obstructive sleep apnea. *Ann Intern Med* 2005;142:187.

Rabe KF, Hurd S, Anzueto A, et al. *Global strategy for the diagnosis, management and prevention of chronic obstructive pulmonary disease*: GOLD Executive Summary. *Am J Respir Crit Care Med* 2007;176:532–555. http://www.goldcopd.org/GuidelinesResources.asp.

Light RW. *Pleural diseases*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2001.

Ryu JH, Olson EJ, Midthun DE, et al. Diagnostic approach to the patient with diffuse lung disease. *Mayo Clin Proc* 2002;77:1221.

Sharma OP, Maheshwari A, Thaker K. Myocardial sarcoidosis. *Chest* 1993;103:253.

Transport Canada Guidelines on the Aeromedical Assessment of Asthma. http://www.tc.gc.ca/CivilAviation/Cam/TP13312-2/asthma/menu.htm.

CHAPTER 13

Clinical Aerospace Cardiovascular Medicine

James R. Strader, Jr., Gary W. Gray, and William B. Kruyer

I was gratified to be able to answer promptly. I said, "I don't know".

—*Mark Twain*

Cardiovascular diseases (CVDs) will always be a major concern for aeromedical disposition and aircrew standards because they are a major health problem worldwide and a leading cause of mortality and morbidity in industrialized nations. Cardiac diagnoses are frequent causes of loss or restriction of licensure for all categories of civilian and military flying. Most requests for special issuance to fly with a cardiac disorder are for cases of coronary artery disease (CAD), including coronary revascularization (e.g., bypass surgery, stent). Cardiac dysrhythmias and valvular disorders are also common causes for medical review of flying eligibility.

Rapid advancements in cardiology present both challenges and benefits to aeromedical applications. This chapter can neither cover all cardiac diagnoses nor cover any in great detail. Topics of key aeromedical relevance will be discussed, including disposition of various electrocardiographic findings, CAD and CAD intervention, valvular disorders, and tachyarrhythmias. These discussions should also serve as an example of an aeromedical approach to other cardiac diagnoses.

A seven-step process for aeromedical decision making of cardiac diagnoses has been previously proposed and is briefly summarized and discussed as follows (1):

1. Establish a threshold of acceptable risk for aeromedically pertinent cardiac events. Annual event rates greater than threshold would be unacceptable for continued flying.
2. Select appropriate aeromedical events for the cardiac diagnosis under consideration.
3. Determine annual event rates for these selected events.
4. Address any special considerations, such as high $+G_z$ or single-pilot operations.
5. If continued flying is a consideration, a recertification policy must be formulated.
6. Other aeromedical endpoints not considered in the second step should be assessed.
7. And finally, consider the impact of medical therapy for the diagnosis being addressed.

In this process, aeromedical decisions are based on percent per year event rates at 1 to 3 years to address short-term safety and possibly at 5 to 10 years to address the longer-term likelihood of a continued aviation career. Data from aircrew populations and carefully selected populations from the clinical literature would be used. Within the selected threshold (e.g., 1% per year), sudden and complete incapacitation (sudden cardiac death, syncope) is of key importance but all events that may negatively affect proper performance of flying duties should be considered.

The earlier process and the following discussions of select cardiac disorders address applications to aviation, especially military and commercial aviation. This process applies readily to other special environments such as space flight while taking into consideration potentially different risk thresholds due to length of the space mission, isolation, and so on.

Aeromedical decision making may involve aircrew with symptomatic, clinical heart disease. For this, helpful clinical literature is usually available. However, aeromedical decision making must often consider aircrew with asymptomatic, subclinical disease for which helpful literature may be lacking or incomplete. And at times, a disease is not under consideration, but rather an abnormal test suggesting presence of disease [e.g., electrocardiogram (ECG) or graded exercise test]. The aeromedical issue then becomes estimating the risk of underlying heart disease and deciding to what extent this risk should prudently be pursued with further testing. These challenges are the bedrock of aerospace cardiology.

DISPOSITION OF ELECTROCARDIOGRAPHIC FINDINGS

A resting 12-lead ECG is required for routine surveillance of many aircrew positions but is somewhat of an enigma. Some ECG findings [e.g., left axis deviation (LAD), ST-T wave changes, and ventricular ectopy] are correlated with advancing age and an increased incidence of CAD and hypertension, and may have some predictive value. Yet, these same findings are often nonspecific, not reflective of underlying pathology, and often not evaluated in a clinical scenario. The aeromedical dilemma is to balance the pursuit of underlying disease against the unnecessary performance of tests, which themselves may prompt further testing.

When a minor ECG abnormality presents, comparison to prior tracings is often very helpful to determine aeromedical disposition. An ECG finding that has been present and stable for several years may not require evaluation, whereas an abrupt, new finding compared to prior ECG tracings may warrant thorough investigation. The diagnostic criteria for each of these findings are not discussed; rather the reader is referred to standard ECG textbooks.

Many ECG findings occur with such frequency and benignity that they may be considered normal variants, which do not require further evaluation. A list of suggested normal variants is in Table 13-1. This is not intended to be an all-inclusive list. Moreover certainly for individual cases, the aeromedical practitioner may choose to further evaluate any of these findings.

Conduction Disturbances

Right Bundle Branch Block

Incomplete right bundle branch block (RBBB) is a common ECG finding and is considered a normal variant (Table 13-1). Complete RBBB, reported in 0.2% to 0.4% of military aviators, has not been associated with increased risk of progressive conduction system disease or other cardiac problems in aviator populations (1,2). Echocardiography may be aeromedically prudent to exclude structural heart disease. If normal, unrestricted civilian and military flying duties may be allowed, including entry into military flying training. Periodic reassessment does not appear to be indicated.

TABLE 13-1

Normal Variant Electrocardiographic Findings

Sinus Bradycardia	Right Axis Deviation
Sinus tachycardia	Indeterminate axis
Sinus arrhythmia	Early repolarization ST segment elevation
Sinus pause of 3 s or less	Nonspecific interventricular conduction delay with QRS width <0.12 s
Ectopic atrial rhythm	Terminal conduction delay (wide S wave)
Wandering atrial pacemaker	Incomplete right bundle branch block
Junctional rhythm	RSR′ pattern in leads V1 and/or V2
Idioventricular rhythm	R wave taller than S wave in V1
First-degree atrioventricular (AV) block	Supraventricular or ventricular escape beats
Mobitz I (Wenckebach) AV block	Rare supraventricular or ventricular ectopy

Left Bundle Branch Block

Reported in 0.01% to 0.1% of military aviators, the prevalence of left bundle branch block (LBBB) increases with age as does the prevalence of CAD and hypertension. Rare in aviators aged 35 years or younger, LBBB became more common with advancing age older than 35 years (1,2). Aeromedical concerns are the association of LBBB with CAD and dilated cardiomyopathy. In the absence of underlying heart disease, LBBB does not present a significant risk for cardiac events, especially in the relatively young, healthy aviator population. Evaluation of underlying disease is required, but accuracy of exercise testing and nuclear myocardial perfusion imaging is limited by the LBBB itself. ECG ST-segment response during graded exercise testing is not interpretable in the presence of LBBB, and myocardial perfusion imaging is often abnormal in the anteroseptal region. Conventional coronary angiography remains the gold standard for definitely excluding underlying CAD, but is associated with inherent risks. Depending on the aircrew position, computed tomographic (CT) angiography might be considered to exclude most significant coronary lesions. However, approximately 25% of lesions may be incorrectly assessed by this method. Detection of coronary calcification should be as useful for screening as in other populations, although data are not available regarding its efficacy in LBBB. Detection of coronary calcification is discussed later in this chapter.

Experience with United States Air Force (USAF) aviators has revealed underlying CAD in approximately 10%, twice the estimated background incidence. Licensing authorities must consider whether initial assessment of LBBB should include invasive or noninvasive coronary angiography. For many years, the USAF has returned aviators with LBBB to unrestricted flying, if coronary angiography and noninvasive testing are normal. Periodic noninvasive reassessment is appropriate, especially if coronary angiography is not performed during initial evaluation. LBBB can be an early manifestation of dilated cardiomyopathy reinforcing the importance of regular follow-up.

Nonspecific Intraventricular Conduction Delay

Nonspecific intraventricular conduction delay (IVCD) is considered a normal variant in otherwise healthy subjects if the QRS interval is less than 120 ms. If the QRS interval is 120 ms or greater, the IVCD is considered abnormal but the risk of underlying disease and prognosis are unclear. Reported prevalence in military aviators is similar to RBBB. If underlying cardiac disease is present, cardiomegaly is often a feature. Evaluation with echocardiography and, at least in older aviators, graded exercise testing with nuclear or echocardiographic stress imaging, should suffice to exclude underlying disease. In the absence of underlying cardiac disease, return to unrestricted flying duties appears indicated. Periodic reassessment may be appropriate.

Left Anterior and Posterior Hemiblock and Bifascicular Block

Prevalence of left anterior hemiblock (LAHB) and left posterior hemiblock (LPHB) has been reported to be 0.9% and 0.1%, respectively, in military aviators (1,2). ECG textbooks often indicate a significant likelihood of underlying cardiac disease, especially for LPHB. This has not been the case in the military aviator population; underlying cardiac disease is uncommon. Prognosis appears to be normal if no underlying cardiac disease is detected by noninvasive evaluation. Return to unrestricted flying duties may then be recommended without future reassessment.

These ECG findings do warrant investigation, especially if new compared to prior ECGs. Extent of evaluation may depend on the age of the individual and overall CAD risk profile. For the young, low-risk aviator (age 35 or younger), echocardiography may be sufficient. For the older or higher-risk aviator, echocardiography and graded exercise testing are recommended. In the absence of abnormal test results, periodic reassessment does not appear to be necessary.

The prevalence of bifascicular block (combination of RBBB and LAHB or LPHB) is not described for aircrew or other healthy populations. Studies of aviators with RBBB, however, have not shown any increased incidence of underlying disease for bifascicular block compared to RBBB with normal axis. Evaluation and disposition of bifascicular block should therefore be comparable to those of RBBB or of hemiblock alone.

Right and Left Axis Deviation

Axis deviations are not conduction disturbances but are discussed here because there is probably considerable overlap between them and the corresponding hemiblocks. Disposition of axis deviation is a common question for the aeromedical practitioner. Concern is whether axis deviation is a marker for underlying disease. Comparison with prior ECGs is helpful. Abrupt axis shifts might be more significant, whereas a gradual leftward axis shift often occurs with advancing age.

Right axis deviation (RAD) and left axis deviation (LAD) were reported in 0.07% and 0.9% of military aviators (1,2). Available reports in aviators do not indicate a concern for increased likelihood of cardiac disease or events. Echocardiography to exclude structural disease is reasonable. Graded exercise testing is a consideration for the older aviator with new-onset LAD. In the absence of underlying disease, unrestricted flying without future reassessment is recommended.

First-degree Atrioventricular Block

As an isolated finding, PR interval prolongation beyond 200 ms is benign in the relatively active, healthy aviator population. It has been reported in approximately 1% of healthy aviators and is felt to be due to increased resting vagal tone. Evaluation is unnecessary for mild PR prolongation. If the PR interval is markedly prolonged, but shortens to normal or near-normal duration during exercise and the ECG is otherwise normal, unrestricted flying duties are appropriate and future reevaluation is not indicated.

Second- and Third-degree Atrioventricular Block

Healthy, young subjects often demonstrate Mobitz I (Wenckebach) atrioventricular (AV) block on 24-hour ambulatory ECG, typically during sleep. Mobitz I AV block is a rare finding on routine 12-lead ECG, reported in only 0.004% of aviator ECGs (1), and is typically considered a normal variant due to enhanced vagal tone. Mobitz II AV block, reported in 0.003% of military aviator ECGs (1), is a risk for progression to advanced and third-degree AV block with possible hemodynamic symptoms and need for permanent pacing. Many specialists would consider even asymptomatic Mobitz II AV block an indication for permanent pacing. This finding should prompt removal from all flying duties.

Third-degree AV block was reported in 0.004% of military aviator ECGs (1), including both acquired and congenital forms. Acquired third-degree AV block should be disqualified from all flying duties due to the risk of bradycardia-related hemodynamic symptoms. Most specialists would consider symptomatic or asymptomatic acquired third-degree AV block an indication for permanent pacing. Congenital third-degree AV block is a more contentious issue. There is very little experience reported for this finding in military and commercial pilots, probably because it is considered disqualifying for initial flying training and licensure. Although these individuals usually do well clinically, an increased risk of sudden death has been reported. Certification for flying duties is not recommended.

Chamber Dilation and Hypertrophy

Atrial Abnormality

Right and left atrial abnormalities were reported in only 0.004% of military aviators (1,2). These ECG findings are nonspecific in the absence of symptoms or signs of underlying disease that is expected to cause atrial enlargement or hypertrophy. In the absence of such clinical evidence of disease or of other ECG changes, evaluation is unlikely to reveal pathology. Echocardiography will suffice for assessment and disposition should be determined by any underlying disease. More likely, echocardiography will be normal or may demonstrate only mild dilation of one or both atria without other abnormalities. This should be considered a normal variant, not requiring further assessment or any flying restriction.

Ventricular Hypertrophy

Right ventricular hypertrophy is an unusual ECG finding in an aviator population and is reflective of underlying disease. Echocardiography should be performed and further assessment and disposition guided by the findings.

Left ventricular hypertrophy (LVH) has repeatedly been shown to predict increased cardiac risk. This is especially true if secondary ST-T wave changes are also present. Therefore, LVH voltage with associated ST-T wave changes should definitely be evaluated and appropriate medical and aeromedical disposition determined by the findings. Hypertension, aortic valve disease, and hypertrophic cardiomyopathy (HCM) would be considerations.

In the aviator population, LVH will more often be present as increased QRS voltage alone, without other ECG signs. Echocardiography will demonstrate whether LVH is truly present. If not present, no further assessment or future reassessment would seem warranted. If LVH is present, physiologic changes due to physical conditioning must be differentiated from a disease process. This is further discussed at the end of this ECG disposition section under **Athletic Heart versus Cardiac Pathology**.

Ectopy—Premature Supraventricular and Ventricular Contractions

Premature supraventricular contractions (PSVCs) include atrial and junctional premature beats. The prevalence of PSVC on ECG in military aviators is less than 1% (1). PSVCs are generally felt to be benign, even when frequent or paired (couplets) and not indicative of underlying disease. In USAF aviators, asymptomatic frequent and paired PSVCs have not been predictive of arrhythmic events or sustained supraventricular tachyarrhythmias (1). When very frequent and paired, PSVCs may be associated with mild symptoms. The aeromedical disposition would then be guided by the symptomatology.

Prevalence of premature ventricular contractions (PVCs) on ECG is also less than 1% in military aviators (1). Frequency and complexity of PVCs increase with advancing age, as does the prevalence of CAD and hypertension. Also, PVCs associated with some cardiac disorders are predictive of an increased risk of adverse cardiac events. Investigation for PVCs may therefore be more appropriate than for PSVCs. However, in USAF aviators, frequent and paired PVCs have not been predictive of sustained ventricular tachycardia (VT) or arrhythmic events, in the absence of underlying cardiac disease (3).

A single PSVC or PVC on an ECG may not warrant evaluation. It may be prudent to evaluate a single PVC in the older aviator and two or more ectopic beats regardless of age. Twenty-four hour ambulatory ECG will quantitate the frequency of isolated ectopy and will document any pairing or tachycardias. The frequency and complexity of ectopy should then guide further assessment (e.g., graded exercise test, echocardiography) as well as aeromedical disposition.

The USAF currently grades ectopy as a percentage of total beats on the 24-hour ambulatory recording. Rare and occasional ectopy (1% or less of total beats) is not further evaluated. Frequent ectopy (>1% up to 10% of total beats) is evaluated with echocardiography and graded exercise testing; one to ten pairs (couplets) per ambulatory recording is similarly evaluated. Very frequent ectopy (>10% of total beats) and frequent pairs (>10 pairs per ambulatory recording) are evaluated more thoroughly for underlying heart disease at a central facility. However, the significance of frequent ectopy and pairing is yet to be well defined.

Prolonged QT Interval

Prolonged QT interval may be due to primary congenital syndromes or acquired secondary to a wide variety of causes. Secondary causes must be excluded by careful history. The most common secondary cause is medication. Additional secondary causes include certain electrolyte imbalances (e.g., hypocalcemia), endocrine abnormalities, neurologic events, and nutritional deficiencies (e.g., associated with chronic alcohol abuse). Congenital long QT syndrome (LQTS) involves many genetically distinct mutations of cardiac ion channels that affect the action potential, causing susceptibility to VT. Currently, several genotypes are described. Inheritance is usually autosomal dominant, but with variable expression. Routine genetic testing for diagnosis is not yet available.

LQTS is essentially an ECG diagnosis. Other factors, primarily symptoms in the patient or relatives, are also helpful for diagnosis. QT interval varies with age, gender, and heart rate and is typically expressed as QTc (QT corrected for heart rate). Normal QTc is usually reported as 440 or less overall. For adult females, QTc greater than 460 is abnormal and QTc greater than 480 is essentially diagnostic. And for adult males, QTc greater than 450 is abnormal and QTc greater than 470 is essentially diagnostic. T-wave changes may also be present and characteristic for specific genotypes of LQTS. A patient may have only a borderline prolonged QTc or even, at times, a normal QTc and still have the LQTS syndrome.

Ambulatory ECG monitoring may demonstrate prolonged QTc and transient T-wave changes at different heart rates. The lethal arrhythmia is polymorphic VT (*torsade de pointes*), but short runs of VT are rarely documented on ambulatory monitoring. Exercise or startle often elicits the arrhythmia, yet it is rarely precipitated by exercise testing. Treadmill testing may help with the diagnosis—QT interval normally shortens during exercise and does not prolong during recovery. With at least some LQTS genotypes, QT interval may prolong significantly during the recovery phase. Electrophysiologic testing, signal-averaged ECG, and other sophisticated tests have not been helpful for diagnosing LQTS or predicting events.

A low-risk subset of LQTS includes subjects with LQTS by ECG and other studies, but no personal or family history of documented or suspected arrhythmic events. Annual event rate for sudden cardiac death or syncope is approximately 0.5% per year. Higher-risk subjects with a positive personal or family history of events have an approximately 5% per year risk of sudden death or syncope and 10% to 20% of first events are sudden death. Presumably, there is also a risk of presyncope and lightheadedness, although rates for these events are not well documented.

Symptoms are often provoked by exertion or startle situations. Other than recommending against competitive athletics, unrestricted activity is generally recommended for asymptomatic subjects, especially if on prophylactic β-blocker therapy. Even symptomatic subjects, whose symptoms are controlled by β-blockers and who have a benign ambulatory ECG recording and treadmill, are generally not activity restricted except from competitive athletics. Aeromedical disposition of LQTS must consider the above risk of arrhythmic events and activity restrictions, particularly with the military aviator, for whom periodic physical fitness testing and other physical activity are often mandatory. These risks probably warrant disqualification from entry into initial flying training. If discovered in an older aviator, who has had no prior events and a negative family history, return to some restricted, low-performance flying duties may be a consideration. For pilots, this should include restriction to multipilot aircraft.

Possible Myocardial Ischemia and Infarction

ECG changes diagnostic for myocardial infarction (MI) should prompt removal from flying duties pending further diagnostic and prognostic evaluation, with disposition determined by the findings. A more common situation will be nondiagnostic changes suggesting a possible MI, such as small Q waves in the inferior limb leads or poor R-wave progression in the anterior precordial leads. Comparison with prior ECGs and repeat ECG with careful lead placement may be valuable. If further assessment is warranted, graded exercise testing alone is not adequate because it may be normal if there is no post-MI residual ischemia. More appropriate would be assessment for regional wall motion abnormalities by echocardiography or a perfusion defect by nuclear imaging. A more thorough evaluation would assess for both MI and residual ischemia either by exercise nuclear imaging or stress echocardiography.

Nonspecific ST-T wave changes can be a dilemma. They do have some predictive value for underlying disease, especially if new compared to prior tracings. However, they are also very nonspecific and the likelihood of significant disease in an otherwise healthy, active and asymptomatic aviator is low. Nonfasting condition can cause transient ST-T wave changes. If the changes persist on a repeat, fasting ECG and are new compared to prior tracings, then screening for CAD may be warranted for the older male aviator (e.g., age 35–45 years) and the postmenopausal female aviator. Younger males with high-risk profiles may also be considered for screening. Graded exercise testing is recommended.

Wolff-Parkinson-White Electrocardiographic Pattern

Wolff-Parkinson-White (WPW) ECG pattern is the classic ECG finding of short PR interval and delta wave without documented or suspected tachyarrhythmias. WPW syndrome is the ECG pattern plus tachyarrhythmia, especially supraventricular tachycardia (SVT). WPW ECG pattern is reported in approximately 1.5/1,000 in both the general population and military aviator populations. Risk of sudden death is 0.1% to 0.15% per year for all WPW subjects; low-risk subsets may be identifiable by electrophysiologic testing. The mechanism of sudden death is considered to be rapid SVT, which deteriorates into atrial fibrillation. If atrial fibrillation is conducted rapidly through the accessory pathway to the ventricle, ventricular fibrillation may ensue. The reported risk of SVT varies widely, but recent data from outpatient community populations and a military aviator population suggest a risk of 1% to 3% per year for at least 10 years after the initial diagnosis of the WPW ECG pattern.

Aeromedical disposition of WPW ECG pattern must consider the low risk of sudden death and the risk for SVT, especially for entry into initial flying training and for military aviation. Radiofrequency ablation will play an important role in some situations and is discussed with tachyarrhythmias in a later section.

Athletic Heart versus Cardiac Pathology

This topic is not exclusively ECG related, but often involves echocardiographic findings of mild dilation of one or more cardiac chambers or mild LVH. However, consideration is often precipitated by increased QRS voltage or other nonspecific ECG findings prompting the echocardiogram. In the absence of underlying pathology and any systolic or diastolic dysfunction, mild dilation or enlargement of one or more of the cardiac chambers is considered a normal physiologic variant, especially in a physically active, asymptomatic individual. No further assessment is recommended.

A common dilemma is mild, concentric LVH on echocardiogram, with or without accompanying LVH voltage on ECG, which may be physiologic hypertrophy or cardiac pathology. Two causes of LVH should be easily excluded or diagnosed. The echocardiogram itself should determine the presence or absence of aortic stenosis. Blood pressure checks should be performed for possible hypertension. If these two causes are excluded, the issue becomes physiologic variant due to physical conditioning versus HCM, an important distinction both medically and aeromedically. Most sources quote 11 mm as the upper limit of normal for left ventricular wall thickness. Left ventricular wall thickness is increased in competitive athletes compared to sedentary controls. Although this increase is usually within the normal range of wall thickness, it is often 12 to 13 mm but rarely exceeds 14 mm. Data from screening echocardiograms performed in military pilot applicants report wall thicknesses up to 12 mm in females and 13 mm in males (1).

In a physically active aviator without hypertension or aortic stenosis, mild, concentric left ventricular wall thickening of 12 to 13 mm may be considered a normal variant. Wall thickness of 14 mm or greater should be further evaluated. Serial echocardiography during abstinence from all exercise should differentiate physiology from disease. Physiologic hypertrophy will regress to normal wall thickness while HCM should not. The aviator must discontinue all aerobic and anaerobic exercise; merely reducing exercise will not cause regression of LVH. Regression is unlikely sooner than 4 weeks after exercise cessation. Continued flying, including high-G flying with straining maneuver, could be continued during this period of exercise cessation.

More than one monthly follow-up echocardiogram may be required. Once regression has been confirmed, the aviator may return to full exercise without requirement for future reassessment.

CORONARY ARTERY DISEASE

According to recent statistics published by the American Heart Association, CVDs, including stroke, CAD, and hypertension, continue to be the leading cause of death in the United States, accounting for more than 40% of all deaths (4). Atherosclerotic CAD is the leading cause of death in the industrialized world. Its importance as a concern for public health as well as aviation safety cannot be overstated. The World Health Organization projects that CVD will be the world's leading cause of morbidity and mortality by 2025.

CAD can present along a continuum from stable angina to unstable angina, MI, and sudden cardiac death. The first presentation of disease can often be sudden cardiac death or MI. Stable angina may be the presenting symptom in only 25% of men, with unstable angina, MI, and sudden death comprising most of the presentations. Any of these symptoms could lead to a decrement in performance or to a catastrophic, sudden incapacitating event. In fact, one half of those who die from an MI do so within 1 hour of symptom onset (5). Sudden cardiac death has been recognized in case reports and anecdotal experience as the cause of loss of life and aircraft in both military and commercial aviation.

Our understanding of the causes and treatment of heart disease has improved dramatically, with death rates from CVD dropping 20% over the last decade. Yet, it remains the major cause of death in industrialized countries. Atherosclerotic burden has been shown to occur at an early age, and clinical events are the late phase of the disease process. Opportunities aimed at prevention should therefore start early in the preclinical state of disease and the identification of those at highest risk must be sought. Cardiology knowledge continues to rapidly evolve with better understanding about the pathobiology of atherosclerosis, identification of novel risk factors, and technologic advances. The milieu in which we operate and the data that emerge lead to great debate on how to effectively screen for CAD, when to perform screening, how to treat, and the prognosis if disease is found. The role that new treatments and detection methods will play on future aeromedical decision making is unknown.

Coronary angiography has been the gold standard for defining the presence and extent of CAD and is properly thought of as a lumenogram. Lesion severity is then defined as percent narrowing of the lumen diameter. Clinically, minimal CAD is usually graded as maximum stenosis less than 50% and significant CAD as maximum stenosis 50% or greater; these definitions will be used in this discussion. However, it must be noted that some literature define significant CAD as maximum stenosis 70% or even 75% or greater. Angiography helps define plaque burden but tells little about composition of plaque. Interestingly, the lumen may appear normal or have only "luminal irregularities" by angiography, yet have significant atheroma within the arterial wall, as detected by intravascular ultrasonography. This has led to the understanding that early in the disease process, the adventitia expands and maintains a constant lumen despite minimal or even moderate plaque within the arterial wall.

Prevalence

In the United States, it is estimated that more than 10 million people currently have symptomatic CAD with an even greater number having asymptomatic disease. Estimated age-adjusted prevalence of CAD in adults aged 20 years or older is approximately 5.5% to 9.0%, depending on gender and race/ethnicity (4). Autopsy studies of young soldiers killed in war have shown evidence of atherosclerosis, with up to 10% having significant lesions. In 1981, a study from the United Kingdom reported similar prevalence of disease between military and commercial pilots who were killed in aircraft accidents. The prevalence of significant CAD in this study was 19% with a mean age of 32 years (1). A review of autopsy studies of commercial pilots showed an age dependency of severe disease prevalence, with 0.6% in pilots younger than 40 years and 7.4% in pilots aged 50 years or older (1). Data from the Royal Air Force reported the prevalence of significant disease by autopsy in private, commercial, and military aircrew as 7% below age 30, rising to 18% at age 30 to 49, and 43% at older than 50 years. Atherosclerosis detected by intravascular ultrasonography performed on donor hearts at the time of cardiac transplantation showed an even higher prevalence, being present in one of six teenagers, one of three aged 20 to 29, and one of two or 50% between the ages of 30 and 39 (6). Aeromedically, CAD is a leading cause of disqualification or denial of licensure in both civilian and military pilots. Aviators as a whole probably have less CAD than the general population but still have a prevalence of disease that warrants concern for detection and treatment.

Pathobiology

Acute coronary events are predominantly caused by plaque rupture or erosion, which is more common in intermediate than in high-grade stenoses. In several studies, one half or more of the sites where MI subsequently occurred had stenoses less than 50%. Although events can occur due to plaque rupture at sites of nonsignificant disease, so-called *vulnerable plaques*, stenoses less than 50% tend to be markers for more extensive disease and therefore poorer prognosis.

The atherosclerotic process is complex and not completely understood. Two initial processes that play important roles in the initiation of atherosclerosis include lipid accumulation and oxidation, along with endothelial dysfunction, caused by coronary risk factors. The initial lesion is a fatty streak, which mainly comprises lipid-laden macrophages. "Vulnerable plaques" are characteristically composed of lipid-rich macrophages with a thin fibrous cap and have less smooth muscle than more mature plaques.

A hallmark of plaque vulnerability is inflammatory cell infiltrates. No modality currently available accurately identifies the vulnerable plaque but this is an area of intense research. Two studies, the Pathobiological Determinants of Atherosclerosis of Youth (PDAY) and the Bogalusa Heart Study, have helped confirm that the process starts in childhood and that CAD prevalence and extent increase with age. In PDAY, all of the aortas and about half of the right coronary arteries in the youngest age-group (15–19 years) had atherosclerotic lesions (7).

Risk Factors

A constellation of risk factors for coronary disease, now termed *traditional or classic risk factors*, were clearly delineated in the Framingham Heart Study and include age, gender, family history of premature CAD, hypertension, smoking, hypercholesterolemia, diabetes mellitus, and LVH. The INTERHEART study identified nine risk factors that accounted for 90% of the risk for MI worldwide, which included smoking, raised ApoB/ApoA1 ratio, hypertension, abdominal obesity, psychosocial factors, lack of daily consumption of fruits and vegetables, daily alcohol consumption, and lack of physical activity (8). Risk factors are often synergistic, such as occurs in the metabolic syndrome.

Other "emerging" risk factors associated with increased risk include homocysteine, lipid fractions such as lipoprotein (a) and apolipoproteins A and B, inflammatory markers such as C-reactive protein (CRP), interleukin 6, and urine microalbumin. The precise role these emerging risk factors will have in screening and risk stratification is yet to be determined, but they may help to determine who should receive more aggressive risk-factor modification.

Although a detailed discussion of all risk factors is beyond the scope of this text, information about some specific risk factors is provided in the subsequent text.

Cigarette Smoking

The evidence linking cigarette smoking to CVD is based on observational studies. Cigarette smoking has been linked to 400,000 premature deaths in the United States annually. A 1989 report from the United States' Surgeon General presented data showing that smoking essentially doubled the incidence of CVD and increased CVD mortality by 50%. Nonsmokers exposed to second-hand smoke are also at a small, dose-related increased risk for coronary disease. Smoking accelerates the atherogenic process in both dose- and duration-dependent manners. Three smoking cessation trials in primary prevention populations demonstrated a 7% to 47% reduction in the rate of CAD events for those who stopped smoking. Smoking status should be a part of routine aviator evaluation. Appropriate counseling and smoking cessation programs should be made available.

Lipid Disorders

Lipoprotein content plays an important role in plaque development and disruption. Both genetic and environmental factors cause dyslipidemias. It is estimated that up to 90% of CAD patients have elevated low-density lipoprotein (LDL) cholesterol, with the majority having only modest elevation. High-density lipoprotein (HDL) cholesterol has an inverse relationship to CAD. In the Framingham Study, low-HDL cholesterol was a much stronger predictor of coronary risk than was increased LDL in subjects older than 50. The total cholesterol-to-HDL cholesterol ratio is the best discriminator between CAD cases and controls. In 1981, a retrospective analysis of USAF aviators examined total cholesterol-to-HDL cholesterol ratio in those who underwent coronary angiography for an abnormal treadmill test. A ratio greater than 6.0 was present in 88% of those with CAD compared to only 4% of those without CAD.

Lipoprotein subfractions may provide additional information about risk. Apolipoprotein B (ApoB) reflects total number of atherogenic lipoprotein particles (very LDL, intermediate-density LDL, LDL, and Lipoprotein[a]) and in some prospective studies it was found to be a better predictor of vascular events than LDL cholesterol. Increased ApoB and high triglyceride levels are more prevalent in patients with the metabolic syndrome and type 2 diabetes.

Lipoprotein (a) is an LDL particle in which ApoB is attached to the Apo(a) protein. Plasma levels of Lp(a) are determined by a single gene and hereditability is high. Lp(a) has been identified as a potent predictor of premature atherosclerosis in most prospective studies (9).

Metabolic Syndrome

The metabolic syndrome comprises a constellation of risk factors including abdominal obesity, dysglycemia, hypertension, and dyslipidemia (with low HDL cholesterol and elevated triglycerides). Diagnostic criteria have been developed by the National Cholesterol Education Panel Adult Treatment Panel III, the World Health Organization, and the International Diabetes Foundation. Of note, the different diagnostic criteria for abdominal obesity differ depending on racial background. The metabolic syndrome increases the risk for cardiovascular events significantly beyond that accounted for by the presence of the traditional risk factors (10) conferring an approximate twofold risk depending on the diagnostic criteria. The underlying mechanism appears to be related to insulin resistance. Risk for development of diabetes mellitus is also significantly increased in individuals with the metabolic syndrome.

Diabetes Mellitus

Diabetes mellitus is a common disorder and recent statistics show it to be increasing in prevalence. Diabetic patients are considered to be at high risk for coronary disease. Atherosclerosis accounts for 75% to 80% of all mortality in diabetic patients, with CAD as the leading culprit. Aggressive treatment of diabetic patients, and especially their other risk factors, is recommended. Military aircrew are usually excluded from aviation duties if diagnosed with diabetes requiring insulin or oral medications, which might cause hypoglycemia. In some jurisdictions, civilian aircrew with diabetes may be licensed for aviation duties. Such individuals require more intensive screening for coronary disease. Further discussion of the approach to flying certification and diabetes, including insulin-dependent diabetes mellitus, may be found under the **Endocrine** section in Chapter 18 and the **Pilot Health and Aeromedical Certification** section in Chapter 11.

Obesity and Physical Activity

Physical inactivity is felt to increase the risk for coronary artery events about twofold. Quantifying the relationship between amount of physical activity and risk is often difficult. Many studies have shown that physical activity reduces the risk of CAD events, especially in men. The greatest cardiovascular risk reduction benefit is obtained when going from inactive to moderately active levels of physical activity, with less benefit going from moderate to extreme physical activity. Exercise improves hypertension control and leads to an elevation of HDL cholesterol. It has been estimated that running 10 mi/wk can increase HDL cholesterol by 25%. A linear relationship has been shown between body mass and mortality, although no study has specifically looked at the effect of weight loss and risk reduction. Typically, obesity is associated with other risk factors and these associations probably mediate its risk.

Family History

Although conventional risk factors explain much of the susceptibility to CAD, approximately 10% to 15% of individuals with CAD have no identifiable risk factors. Family studies in identical twins are consistent with premature CAD being strongly influenced by genetic factors (11). Among identical twins, premature cardiac death confers an eightfold increase in risk to the surviving male siblings and a 15-fold increase to female siblings. In the Framingham Offspring Study, parental cardiac disease led to an approximately twofold increase in risk (12).

Inflammatory Markers

Inflammation has been identified as a key element in the pathogenesis of atherosclerosis, and various markers of inflammation have been studied as indicators of atherosclerotic risk (13,14). These include inflammatory cytokines (e.g., interleukin-6), acute phase reactants such as CRP, with a high sensitivity assay-hs-CRP, and urinary microalbumin (e.g., creatinine-to-microalbumin ratio). Data from Women's Health Study and multiple other prospective studies have demonstrated hs-CRP as an independent predictor of cardiac events. The utilization of hs-CRP (and other markers of inflammation) in risk assessment remains somewhat controversial, but most data support the use of hs-CRP in further stratification of individuals assessed as intermediate risk through traditional risk factors.

Risk Assessment and Risk Stratification

As part of periodic medical screening or certification medical examinations, basic risk factor information should be assessed in military aircrew and civilian license holders to allow estimation of cardiovascular risk. Risk indices have been developed in North America (e.g., Framingham Heart Study), Europe (PROCAM study), and elsewhere, which utilize major risk factors to assess global cardiovascular risk. Risk engines are available on-line or in hard copy to calculate risk (http://www.nhlbi.nih.gov/guidelines/cholesterol/; http://www.chd-taskforce.com/).

Clinical guidelines generally stratify risk as low, intermediate, or high based on Framingham risk scores of less than 10%, 10% to 19%, and 20% or greater. Risk scores may be modulated upward with other risk factors, such as diabetes (high-risk equivalent), metabolic syndrome, or with a family history of early CAD. In intermediate-risk individuals, assessment of emerging risk factors including Lp(a), hs-CRP, ApoB, and urinary albumin/creatinine ratio may help further stratify risk as higher or lower.

Primary Prevention

Military flight surgeons and civilian aerospace medicine practitioners have dual roles, which include responsibilities for medical flight certification and opportunities for preventive medical intervention. In many cases, mandatory periodic medical screening or certification represents the only interface of aircrew with the medical system. Such opportunities should be leveraged to obtain a comprehensive cardiovascular risk assessment.

Risk stratification based on risk indices such as Framingham identifies individuals at increased global risk. Such assessments can be clinically useful for identifying aircrew at intermediate or high risk who warrant immediate attention and intervention. Risk assessments can also serve as a motivation to adhere to risk-reduction therapies.

An important point is that such indices serve as models for risk assessment, but they do have limitations. Many individuals at low or intermediate 10-year risk are at high risk in the long term due to the cumulative effects of a single risk factor, which can lead to premature CAD if left untreated. This means each major risk factor deserves intervention, regardless of short-term absolute risk. Furthermore, the risk indices do not take into account newer risk factors and may therefore indeed underestimate the risk of a given individual. Preventive efforts should target each major risk factor. The centerpiece of long-term risk reduction is modification of lifestyle habits with physical activity, weight control, smoking cessation, and proper diet.

Numerous clinical trials have demonstrated the efficacy of cholesterol lowering in primary and secondary prevention. Early trials such as West of Scotland Coronary Prevention Study (WOSCOPS) and Air Force/Texas Coronary Atherosclerosis Prevention Study (AFCAPS/TexCAPS) demonstrated clear efficacy in primary prevention with a 30% to 40% reduction in relative risk for nonfatal MI or coronary deaths. Other trials of secondary prevention in patients with established coronary disease, for example, Scandinavian Simvastatin Survival Study (4S), Cholesterol and Recurrent Events (CARE), and Long-term Intervention with Pravastatin in Ischemic Disease (LIPID) demonstrated the overwhelming benefit of lipid-modifying treatment in secondary prevention. When comparing primary and secondary trials, there was no significant difference in relative efficacy, only in absolute event rates (i.e., secondary prevention gives "more bang for the buck"). These trials support the role of aggressive lowering of LDL cholesterol in patients with documented CAD, along with aggressive lowering in patients with multiple risk factors or high-risk lipid profiles but without known disease. In recent secondary prevention trials (e.g., PROVE-IT), incremental benefit has been shown with intensive lipid lowering to LDL cholesterol targets less than or equal to 70 mg/dL.

All classes of lipid-lowering medications are in general compatible with flying duties. On initiation of treatment, a nonflying observation period of approximately 1 week is prudent to observe for idiosyncratic reactions. Statins and fenofibrates, particularly in combination, may cause myalgias or rarely, frank myositis. Concomitant use of antifungal drugs and macrolide antibiotics also increases the risk for myopathy. Patients should be cautioned to report any suspicious symptoms immediately, and creatinine kinase levels should be assessed if symptoms warrant. Statins and niacin may cause significant elevation of hepatic transaminases, and measurement of transaminase levels before and after initiating treatment is advised. A suggested protocol, currently used by the USAF, is to check hepatic transaminases before starting therapy, after 12 weeks of therapy, annually, and when clinically indicated. Creatine kinase could be obtained before therapy and when clinically indicated. In some jurisdictions [e.g., USAF, United States Navy (USN)], a waiver is required for certain classes of lipid-lowering medications, and some (e.g., niacin) are not allowed.

Guidelines for primary and secondary prevention have been published by several expert panels (15–17) and should be consulted for specific recommendations. A disturbing fact is that therapy is underutilized, with more than 80% not receiving therapy for secondary prevention and only 4% of primary prevention eligible patients receiving therapy (1,5). We in the medical profession are not adequately treating those who would benefit the most.

Screening for Coronary Artery Disease

The prevalence of asymptomatic CAD greatly exceeds that of established CAD. A major, often catastrophic event may be the initial presentation of coronary disease in up to half of previously asymptomatic individuals. Detection of asymptomatic CAD should facilitate initiation of more aggressive preventive measures to mitigate the risk of a major coronary event. Screening tests which detect asymptomatic CAD therefore have a dual role in prolonging and improving quality of life, and in reducing risk for occupational mishaps.

Screening tests for CAD are intended to detect flow-limiting, hemodynamically significant obstruction, or to detect the presence of coronary plaque. Tests for obstructive coronary lesions include exercise stress testing, stress nuclear perfusion imaging (NPI), and stress echocardiography. Techniques for plaque detection include tests for quantitative assessment of coronary artery calcium scores (CACS) utilizing electron beam computed tomography (EBCT), or multidetector computed tomography (MDCT). With the development of more sophisticated technology, with some limitations, CT contrast coronary angiography with MDCT provides information regarding both plaque burden and coronary lumenograms of a quality approaching conventional coronary angiography.

The utility of screening tests is related to the sensitivity and specificity of screening techniques, and to Bayes' theorem. Test sensitivity reflects the ability of a screening test to detect the disease when present. Specificity reflects the test ability to correctly identify the absence of disease. Bayes' theorem relates the post-test probability of the presence of disease to the prevalence in the population, or pretest probability. When the pretest probability is low, as is the overall prevalence of CAD in an aviator population, the post-test probability after a positive screening test remains low, with a low positive predictive value. Therefore, general screening of an aviator population with tests for obstructive coronary disease (stress testing, stress NPI, or stress echocardiography) is not recommended without prior risk stratification. Application of tools utilizing risk factor analysis (e.g. Framingham and other risk factors as discussed earlier) identifies individuals in whom the pretest probability is higher, and in whom secondary screening tests will have a greater utility. Individual aviation authorities must decide what level of pretest probability should trigger secondary screening testing. Generally, this is reserved for aviators identified as being at "high risk" based on risk factor analysis. However, the risk level identified for triggering secondary screening may relate not only to aviation safety but also to mission risk management, with a lower threshold, for example, in a long-duration space crewmember or a high-performance military aviator.

The choice of test for screening depends on availability, expertise, cost, and operating characteristics of the test (sensitivity, specificity). Tests with higher sensitivity will detect the disease more often when present, with fewer "false negatives." Higher specificity will be reflected in fewer "false-positive" results. An important consideration in determining aeromedical disposition is the prognostic value of a negative screening test. A recent meta-analysis indicated that in individuals with a normal exercise NPI or stress echocardiography study, event rates for MI or cardiac death were less than 0.6% per year over the following 3 years (18). USAF data comparing exercise treadmill, thallium NPI, and cardiac fluoroscopy showed event rates 0.5% per year or less over 5 years of follow-up for all three modalities.

Stress Testing

Exercise stress testing assesses for obstructive, flow-limiting coronary artery lesions and additionally provides information about blood pressure response, arrhythmias, and aerobic capacity. It has the advantage of being both safe and widely available. The sensitivity and specificity of exercise stress testing for hemodynamically obstructive lesions is approximately 60% to 70%; therefore, application in a population with low-disease prevalence results in large numbers of false-positive results, requiring further investigation to clarify. Sensitivity and specificity may be lower in women.

Current recommendations by an expert committee are that exercise stress testing is a Class IIb indication (reflecting conflicting evidence or divergence of opinion) in asymptomatic men older than 45 years and for women older than 55 years involved in special occupations, such as aviation, in which impairment might affect public safety (19).

In an unselected military aviator population, the positive predictive value of an abnormal stress test for significant angiographic CAD was only 10%. Preselection by abnormal resting ECG doubled the positive predictive value to approximately 20% (1). A prospective study of treadmill testing in 25,927 apparently healthy, asymptomatic men with a mean age of 43 years showed that an abnormal treadmill test had an age-adjusted relative risk for CAD of 20. This increased sequentially as the number of risk factors increased (age-adjusted relative risk of 80 with three or more risk factors). They concluded that exercise testing was a worthwhile tool to predict future risk of CAD death, especially in those with more cardiac risk factors (20).

Nuclear Testing

NPI assesses the perfusion-dependent distribution of isotopes in the myocardium at rest and after stress. NPI with an isotope such as thallium or technetium improves the sensitivity and specificity of stress testing to approximately 85% to 90%. Stress may be induced either through exercise treadmill, cycle ergometry, or pharmacologically, as with dobutamine infusion. Because of the additional cost and radiation exposure involved, NPI is generally utilized in individuals with abnormal treadmill tests or baseline ECG abnormalities that preclude diagnostic ST changes (e.g., LBBB).

Multiple gated acquisition scans (MUGA) provide information about global ventricular function (measurement of ejection fraction) and segmental wall motion abnormalities, and may complement information provided by NPI studies.

Stress Echocardiography

Stress echocardiography assesses segmental and global myocardial contractility at rest and with stress. This is assessed by imaging the myocardium and endocardium. Stress may be accomplished with an exercise treadmill, supine bicycle exercise, or pharmacologically (e.g., dobutamine infusion). Sensitivity and specificity are similar to stress NPI (21). Limitations include technical difficulties in accurate imaging of all myocardial segments, which may be improved with injection of contrast agents that opacify the ventricles. Stress echocardiography may be particularly useful in women, avoiding radiation exposure while providing a more sensitive testing modality than stress testing, which has decreased sensitivity in women. Stress echocardiography may also be useful as a follow-on screen in individuals with positive stress tests.

Tests which Assess for Coronary Plaque

With the evolution of our understanding of the pathogenesis of CAD from the initial formation of atherosclerotic plaque, progressing slowly over time to flow-limiting obstructive lesions, the detection of early plaque lesions became appealing. The presence of calcium deposition in the coronary arteries almost always reflects the presence of coronary plaque, although earlier in evolution, plaque may not be calcified.

Coronary artery fluoroscopy (CAF) has been used since the 1960s and has been relatively accurate to predict the presence of anatomic atherosclerotic disease. CAF is a nonquantitative assessment for coronary calcium. In studies by the US Army and USAF, coronary calcium detected by CAF has been shown to have a higher positive and negative predictive value for obstructive coronary disease and coronary events than exercise stress testing or stress thallium, with a sensitivity and specificity of 70% to 75% (22,23).

Coronary artery calcium can be measured quantitatively by CT scanning techniques, which are coupled with ECG gating to overcome the problem of cardiac motion during acquisition. EBCT uses an electron sweep of stationary tungsten rings that generates rapid radiographic images. Multislice computed tomography or multidetector computed tomography (MSCT/MDCT) utilizes a gantry of multiple rapidly rotating CT scanners with rapid rotation (300–400 ms). Current generation MDCTs utilize up to 64 slices, with future generations already in development. EBCT and MDCT produce similar scores, except at very low score levels. Radiation exposure with MDCT is significantly greater than EBCT.

CACS results are quantitatively expressed in Agatston units. Normative data has been established in large data sets (24). Quantitative coronary calcium scores reflect overall plaque burden and have been demonstrated in both retrospective and prospective studies to provide incremental prognostic information for coronary events beyond that acquired from standard risk data. CACSs greater than 100 are considered to represent a threshold above which coronary events are more likely, with asensitivity, specificity, and odds ratio at 89%, 77%, and 25.8%, respectively (25). However, the presence of any coronary calcium reflects the presence of coronary plaque, and in conjunction with other risk factor data may guide the intensity of preventive measures (e.g., lipid-lowering targets) and further diagnostic evaluation.

Utilizing intravenous contrast, MDCT is capable of providing high-quality almost-instant noninvasive coronary angiography, with high diagnostic accuracy for the assessment of coronary artery stenoses and the identification and characterization of coronary plaques. Limitations include motion artifacts and heavily calcified coronary artery segments. MDCT coronary angiography technology is rapidly reaching a maturity level sufficient to provide accurate, noninvasive angiographic information in aviators in whom other noninvasive testing suggests the presence of coronary disease, or who are being assessed for possible return to aviation duties following revascularization or MI. An additional feature of MDCT angiography is the capability of identifying noncalcified plaque, which may help guide the intensity of preventive intervention as well as coronary risk assessment.

Which test to use to further screen aviators in whom primary risk stratification triggers a requirement for secondary screening will depend on factors such as cost, availability, and the performance characteristics of the test. Exercise stress testing is widely available but has the lowest sensitivity and specificity, and will frequently produce false-positive results in a low-prevalence population. Stress echocardiography and NPI tests have a higher sensitivity and specificity, but are more expensive and are often reserved for further assessment of individuals with positive exercise stress tests. Assessment of CACSs by EBCT or MDCT is increasingly available, and provides the most sensitive and specific information about the presence of coronary plaque and related risk for coronary events. CT coronary angiography involves higher radiation dose exposure but provides definitive information about coronary plaque and lumen, and is best reserved for positive results with other testing modalities.

In the selection of crewmembers for long-duration space missions on the International Space Station (ISS), CACS screening is included in the primary screening process, along with traditional risk factor information and hs-CRP. Candidates with CACS greater than 100 or greater than the 90th age- and gender-matched percentile are required to undergo further testing which includes coronary angiography. The presence of angiographic coronary disease is disqualifying for long-duration mission assignment. CACSs are repeated every 5 years in ISS crewmembers.

Women and Coronary Artery Disease

Historically aviation as a whole, and especially military aviation, has been a male-dominated profession. Most aviation medicine literature therefore relates to the male aviator population, and especially the male pilot population, and may not be applicable to the growing female aviator population. This is particularly true for CAD. In the USAF, the number of female candidates screened for flying training has been approximately 10% since 1994. Much publicity is given to gender-specific problems, such as breast cancer and osteoporosis. However, as with men, CVD is the leading cause of mortality and morbidity in women. CVD is responsible for one third of all deaths of women worldwide, and half of all deaths of women older than 50 years in developing countries (26). The lifetime risk of developing CAD after age 40 is estimated as 49% for men and 32% for women (4). Several authors have expressed CAD as "an equal opportunity killer." The caveat is that CAD generally presents approximately 10 years later in women than in men.

Some research indicates that CAD is less aggressively pursued and treated in women than in men (a phenomenon described as the *Yentl syndrome*), and cardiovascular health in women is not improving as fast as that of men. However, the aeromedical emphasis in women, as in men, is on risk assessment of known or suspected CAD as it relates to safe continuation of flying duties.

Clinically, CAD often presents differently in women than men. Women have smaller coronary arteries and less collateral circulation than men, which may lead to an increase in ischemia, particularly during exertion or stress. Framingham data indicate that 69% of women initially present with unstable angina compared with 30% of men. Atypical prodromal symptoms in women include fatigue; difficulty breathing, shortness of breath and dyspnea; neck and jaw pain; palpitations; cough; nausea and vomiting; and indigestion.

Although the same cardiac risk factors generally apply to women as they do to men, there appear to be some gender differences with respect to risk factors. Smoking rates are higher in men. The prevalence of obesity and associated insulin resistance is higher in women and they tend to be less physically active than men. Before menopause, women have better risk profiles than men, with lower blood pressures and LDL cholesterol levels and higher HDL cholesterol levels. Some of these differences are thought to be mediated through sex hormones and, following menopause, risk profiles of men and women become more similar.

Risk factor modification works for both women and men. Recent statin trials have clearly demonstrated that the benefits of lipid modification apply to women as well as men, for both primary and secondary prevention of CAD. After menopause, the risk for CAD rises sharply in women. Hormone replacement therapy, once thought to be protective, was shown in the Women's Health Study to increase cardiovascular risk. Although many beneficial effects on risk factors and CAD markers have been demonstrated, the rate of CVD is not decreasing in women as well as it is in men. However, the standard efforts of smoking cessation, weight control, regular exercise, detection and control of diabetes and hypertension, and management of dyslipidemia are clearly effective for women. Nonpharmacologic and pharmacologic risk factor modification should be aggressively pursued in aviators of both genders.

The screening tests discussed earlier were mostly related to male subject populations; good data on female populations, especially female aviators, is still lacking. ECG response on treadmill testing is reportedly less reliable in women, resulting primarily in more false-positive tests, a problem especially of concern for aeromedical issues. Myocardial perfusion imaging with thallium or other agents is more accurate than treadmill alone, although false defects due to breast attenuation are a problem. Stress echocardiography is reportedly more accurate and cost effective for CAD screening and evaluation of chest pain syndromes in women. The overall prognostic value of coronary plaque load assessed by CT coronary artery calcium scoring does not appear to be affected by gender, but coronary calcium scores are lower in premenopausal women than age-matched men and gender-specific normative data should be used when assessing risk.

These influences of gender on risk factors and primary prevention, the application of secondary screening technologies, and the potential atypical symptomatic presentations must be considered by the aeromedical practitioner and by licensing authorities when evaluating female aviators for suspected or known CAD. Further discussion may be found under the section **Women's Health Issues** in Chapter 22.

Natural History and Aeromedical Disposition

CAD is typically a progressive disease in two respects; established lesions become more stenotic and new lesions develop. The true natural history of CAD is unknown because most patients with diagnosed CAD are on medical therapy and/or have had coronary revascularization. In general, cardiovascular risk factors related to the incidence of CAD also contribute to the prognosis after an event. Aggressive secondary prevention is therefore extremely important, both clinically and aeromedically. Natural history data on aviators with CAD is sparse. Compared to the general population, aviator groups are generally healthier, with fewer risk factors, and are often asymptomatic. Aeromedical decisions regarding CAD are usually based on data from clinical populations, which may or may not apply well to aviators. Also, the state of knowledge in the clinical realm of diagnosing and treating disease is rapidly evolving. Aspirin use, better treatment of hypertension, and aggressive therapy for lipid abnormalities, especially with statins, may significantly alter the statistics from which current opinion is rendered.

Despite its imperfect assessment of disease extent, coronary angiography does predict intermediate and long-term outcomes. Several studies have shown that the extent of anatomic CAD is a strong predictor of survival and other clinical events. Current recommendations of many aviation regulatory agencies consider this and allow varying degrees of CAD to maintain licensure, although often restricted. Civilian and military aviation policies regarding return to flight duties involve very different missions, including combat and high-performance flight for the military. If certain degrees of CAD are allowed to return to some categories of flying, policies should also place a greater emphasis on secondary prevention.

Several groups have performed long-term follow-up of apparently healthy civilian populations and patients with normal coronary arteries by angiography, reporting annual cardiac event rates of 0.0% to 0.65% per year over 10 years (1). A review of apparently healthy USAF aviators showed a 5-year annual cardiac event rate that increased progressively with age, but only up to approximately 0.15% per year for the oldest age-group of 45 to 54 years (27). These "normal" cardiac event rates may be compared to those for minimal and significant CAD for the purpose of aeromedical decision making.

Minimal Coronary Artery Disease

Long-term studies of minimal CAD (maximum angiographic lesion <50%) report annual cardiac event rates of approximately 1.5% to 3.0% per year over approximately 10 years of follow-up. Moreover, event rates increased progressively with increasing severity of nonsignificant disease. In these studies, the cohort of patients typically had a chest pain syndrome that ultimately led to coronary angiography. In contrast, USAF experience with approximately 250 asymptomatic military aviators with minimal CAD showed an event rate of approximately 0.5% per year over 10 years of follow-up. In the Coronary Artery Surgery Study (CASS) registry, a subset of 6,758 patients had no significant coronary stenoses. In this subset, 4,463 had normal coronary angiography, 1,368 had at least one minimal (30%–50%) lesion, and 927 had at least one moderate (50%–70%) lesion. In CASS, significant CAD was defined as maximum lesion greater than 70%. Survival at 12 years was 91%, 86%, and 79% for normal coronary angiography, minimal lesions, and moderate lesions, respectively (28).

Given the low event rate in their aviators with minimal CAD, the USAF has for years allowed such members to continue to fly, restricted to low-performance, multipilot aircraft, if they are asymptomatic and have had no prior cardiac events. The effects of high $+G_z$ forces on minimal lesions are unknown and most high-performance aircraft are single seat. Plaque rupture of even minimal lesions and asymptomatic progression to significant CAD are additional concerns. Return to multipilot commercial flying and general aviation is also recommended. Periodic noninvasive evaluation is recommended, annually for military aviators. The rate of progression of minimal CAD to significant CAD is unknown. Pending more reliable noninvasive methods to detect asymptomatic progression and better data in aviator populations with minimal CAD, periodic repeat coronary angiography (3- to 5-year intervals) is a consideration, depending on extent of disease, stability of noninvasive testing, control of modifiable risk factors, and type of flying duties.

Significant Coronary Artery Disease

In the CASS registry, overall 4-year survival rates for medically treated patients with zero-, one-, two-, and three-vessel significant CAD were 97%, 92%, 84%, and 68%, respectively, and 12-year survival rates were 88%, 74%, 59%, and 40%, respectively. Again, CASS defined significant CAD as a lesion stenosis equal to 70% or more. Angiographic extent of disease was the most important variable in determining 4- and 12-year survival rates. Another powerful predictor of survival was the status of left ventricular function (28). Reported annual mortality rates for all categories of significant CAD combined are approximately 3.0% to 4.0% per year. In some of these studies, as with CASS, maximum stenosis of 70%, rather than 50%, was the criteria for significant disease. The USAF compared cardiac event rates in a subset of 92 military aviators with minimal to moderate CAD (maximum lesion 40%, $n = 38$, versus maximum lesion 50%, $n = 54$). For the 40% group, the annual cardiac event rate was approximately 0.5% per year at both 5- and 10-year mean follow-up, with no cardiac deaths. For the 50% group, the annual cardiac event rate was approximately 3.0% per year at 5 years and 2.5% per year at 10 years, with one cardiac death. In most studies, event rates are also correlated with the number of arteries involved, whether the left main coronary artery is involved, and the status of left ventricular function.

One of the most compelling aeromedical concerns is disease progression, especially development of new significant lesions (≥50% stenosis) in artery segments that previously appeared normal by angiography. The Medicine, Angioplasty, or Surgery Study (MASS) was a prospective trial of patients with symptomatic single-vessel (left anterior descending artery) significant CAD who were randomized to medical treatment, angioplasty, or surgical bypass with an internal mammary artery graft. Development of new significant lesions occurred in 30% to 35% of patients at 2 years, regardless of treatment group (1,29). At 5 years, new significant lesions appeared in approximately 60%, 50%, and 45% of those treated medically, by angioplasty and by surgery, respectively. And in the medically treated group, the annual cardiac event rate was 4.8% per year at 5 years (29).

Without revascularization (e.g., angioplasty, stent, bypass surgery), return to flying is generally not recommended for significant CAD (maximum stenosis ≥50%). Return to restricted civilian or military aviation might be considered for single-vessel moderate disease (maximum lesion 50%–70%) with limited minimal disease at other sites. The aviator should be asymptomatic, without evidence of ischemia in the distribution of the significant lesion, and off antianginal medications. Overall, left ventricular function should be normal without regional wall motion abnormalities. In USAF experience, military aviators meeting these criteria had average annual event rates of approximately 1.0% per year. Annual noninvasive reevaluation is recommended. Repeat coronary angiography at 3- to 5-year intervals is a consideration. Further discussion of civilian issues may be found in Chapter 11.

Percutaneous Coronary Intervention

The standard treatment of CAD has been medical, surgical bypass, and percutaneous coronary interventions (PCIs), aimed at secondary prevention of events and relief of symptoms. PCI is the current term for nonsurgical, catheter-based coronary revascularization, such as angioplasty and stents. Coronary revascularization, surgical or PCI, has typically been disqualifying for military aviation duties. However, commercial aviation licensing agencies often allow return to flying duties for select lower-risk individuals after successful revascularization procedures.

A number of percutaneous modalities have emerged since the late 1970s when percutaneous transluminal coronary angioplasty (PTCA) was first used. PCI includes PTCA, directional atherectomy, rotational atherectomy, laser-guided procedures, and coronary artery stents. The specific indications of each procedure will not be discussed. With the advent of PCI, the mortality and MI could be reduced. For most patients with one- or two-vessel CAD, multiple trials have repeatedly shown no significant benefit regarding survival or MI for PCI compared to medical therapy.

The main problem with PCI has been short-term restenosis at the treated site, typically occurring within 3 to 6 months after PCI. Restenosis occurs in approximately one third of all angioplasties, when defined as return of symptoms, and may be as high as one half when defined angiographically. Restenosis rate is reduced to 10% to 20% or less with the use of coronary stents, especially drug-eluting stents. Prediction of subsequent cardiac events based on the degree of restenosis has been difficult.

Another major problem is that native vessel disease is often present in other locations and may progress or lead to acute clinical events due to plaque rupture. Also, PCI of moderate disease may lead to a more severe stenosis with a significant incidence of restenosis and worse clinical outcome. Studies of asymptomatic patients treated with PTCA have shown no significant change in exercise tolerance and no significant reduction of future symptoms, revascularization, MI, or cardiac death. Performing PCI on asymptomatic aviators only for occupational purposes and without standard clinical indications may not be advisable.

Recent PTCA and stent trials report annual cardiac event rates (cardiac death or nonfatal MI) of approximately 1% to 2% per year for successful/uncomplicated PCI of one-vessel and most two-vessel diseases (1). Annual cardiac event rates are approximately doubled if angina and repeat revascularization are added. For the PTCA arm of the MASS trial, the annual event rate at 5 years of follow-up was approximately 8% per year; for cardiac death or nonfatal MI it was slightly above 2% per year. However, most repeat revascularizations were performed for unstable angina (29). Much of this literature involves PTCA. In more recent stent trials in low-risk patient subsets, event rates have been in the range of 1% to 3% per year, some even less than 1% per year.

Return to restricted flight duties in multipilot, low $+G_z$ aircraft may be acceptable for select pilots who have undergone PCI of a native vessel, who have no significant restenosis, no evidence of reversible ischemia, and preserved left ventricular function. Initial assessment should be at least 6 months after PCI. Coronary angiography is recommended as part of the initial evaluation if return to flying is being considered for commercial or military aviation. Noninvasive reevaluation should be performed at least annually. Periodic repeat coronary angiography at 3- to 5-year intervals is again a consideration.

Coronary Artery Bypass Surgery

Coronary artery bypass grafting (CABG) is very effective treatment for reducing the symptoms of angina. And, in select groups such as three-vessel disease, it has significant mortality benefit. However, the disease process is still present after CABG, with progression of native vessel disease along with disease development in the grafts, primarily in saphenous vein grafts, which have a reported annual failure rate of approximately 3% per year. This emphasizes the point that CABG is only palliative, not curative. Graft patency is significantly improved, as is survival, with the use of the internal mammary artery as a graft conduit. Risk factors that lead to CAD, especially lipids and smoking, significantly affect outcome after CABG. Subjects considered for CABG for established clinical indications will usually have significant two- or three-vessel disease and many will have had previous MI or reduced left ventricular function. Graft occlusion and progression of native disease are the primary concerns.

Annual event rates in the first few years post-CABG generally exceed 2% per year. For low-risk groups post-CABG, annual event rates for only cardiac death or nonfatal MI are approximately 1% to 2% per year, compared to 5% per year or greater for moderate- to high-risk groups. Adding other endpoints, such as angina and repeat revascularization, approximately doubles the annual event rates to 3% to 4% per year for low-risk groups. Select low-risk groups may have annual event rates as low as 0.5% to 1.0% per year for cardiac death or nonfatal MI (1). For the surgical arm of the MASS trial, annual event rate at 5 years was 1.7% per year; all events were fatal or nonfatal MI (29).

As with PCI, return to civilian flying has been allowed by licensing authorities for years. Return to restricted flight duties in multipilot, low $+G_z$ aircraft may be acceptable for select military aviators post-CABG. As with PCI, there should be preserved left ventricular function and no evidence of reversible ischemia off cardioactive medications. Initial assessment should be at least 3 to 6 months after CABG. Coronary angiography is recommended as part of the initial evaluation if return to flying is being considered for commercial or military aviation. All grafts should be patent and all significant lesions should be grafted (complete revascularization). Noninvasive reevaluation should be performed at least annually. Periodic repeat coronary angiography is again a consideration. Civilian aeromedical certification issues are covered in Chapter 11.

Myocardial Infarction

The mortality rate associated with CAD has declined but the number of acute MIs has remained relatively constant. Prognosis is complex depending primarily on the status of left ventricular function and severity of underlying CAD. Aeromedical disposition post MI is affected by these factors and several others, such as revascularization post MI, patent versus occluded infarct-related artery, success of secondary preventive efforts, and residual ischemia. Presence of a prior MI increases the event rate for all significant CAD groups, with or without revascularization. Recommended post-MI medications must also be considered. Most guidelines recommend statin, β-blocker and angiotensin-converting enzyme (ACE) inhibitor therapy post MI unless specifically contraindicated. Any consideration of return to flying post MI must be tailored to the individual clinical scenario and the type of aviation.

HYPERTENSION

Hypertension is an established and important risk factor for CVD, especially stroke and CAD, contributing to increased mortality in men and women of all ages and ethnic groups. It also leads to other significant complications such as peripheral vascular disease, end-stage renal disease, and heart failure. Numerous studies have documented a continuous relationship between the level of blood pressure and risk, for both systolic and diastolic pressure. Like CAD, hypertension is a complex disease modified by both genetic and environmental determinants. Most hypertensives are classified as essential, meaning that no definable pathologic process is apparent as the etiology. Hypertension has generally been defined as a blood pressure greater than 140/90 mm Hg.

Classification and Evaluation of Hypertension

The classification of hypertension has changed with increased understanding of the risk of high blood pressure along a continuum. The Seventh Report of the Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure (JNC 7) offers excellent background information as well as recommendations for classification, risk stratification, and therapy. As most hypertensive subjects are asymptomatic, blood pressure should be recorded on each health care encounter. Diagnosis of hypertension should take into account at least three blood pressure readings taken on different days.

JNC 7 continues to define hypertension as systolic pressure greater than or equal to 140 mm Hg, diastolic pressure greater than or equal to 90 mm Hg, or requirement for chronic medication to control blood pressure. A new category, prehypertension, is 120–139/80–89 mm Hg and normal or optimal blood pressure is less than 120/80 mm Hg. Lifestyle modifications are recommended for prehypertension. Control of treated hypertension is generally defined as less than 140/90 mm Hg. Lower thresholds for medication and lower treatment target levels are recommended for higher-risk patient groups as well as for those with additional risk factors, target organ effects, or diagnosed CVDs.

After diagnosing hypertension, routine evaluation should include medical history, physical examination, and routine laboratory tests. History should focus on duration of disease, symptoms, current medications, lifestyle habits, and comorbid conditions. Physical examination should focus on other areas of vascular disease—bruits, pulses, S4 on cardiac auscultation, and hypertensive retinal changes, as well as changes suggestive of secondary hypertension (e.g., renal artery stenosis, endocrine causes for hypertension etc.). Laboratory tests should include serum electrolytes, complete blood count (CBC), lipid profile, fasting glucose, and creatinine. ECG should be performed, looking for signs of LVH or manifestations of CAD.

White Coat Hypertension

Blood pressures may be elevated in the physician's office, then appear normal on subsequent checks, a condition often called *white coat hypertension*. Many investigators have addressed the significance of white coat hypertension. This is still debated as studies have emerged on both sides of this issue. Data indicate that true hypertension is worse than white coat hypertension regarding clinical course and end-organ damage. However, white coat hypertensives are at greater risk than normotensives. This entity must not be considered just a normal variant. It might more appropriately be considered labile hypertension or prehypertension. Lifestyle modifications should be instituted, although pharmacologic therapy may not yet be indicated.

Aeromedical Disposition and Summary

Hypertension itself does not carry the risk of sudden incapacitation. The obvious concern for the aviator community is its risk for stroke and heart disease, which can be suddenly incapacitating. Exposure to the high $+G_z$ environment has not been shown to pose a risk for developing hypertension. Failure to diagnose and treat hypertension appropriately in the interest of a flying career does the aviator a disservice. JNC VII guidelines are well recognized and accepted; they are also readily adapted to aeromedical policies and disposition. Current USAF policy allows continued flying duties if blood pressure is controlled nonpharmacoligically or by approved medications to less than 140/90 mm Hg and there is no evidence of end-organ damage. For initial blood pressure greater than 140/90 but less than 160/100, a 6-month trial of nonpharmacologic therapy (lifestyle modifications) is allowed, with the aviator remaining on flying duties. Currently approved medications for USAF aviators are thiazides and lisinopril. Aviators started on medical therapy should have an initial grounding period, usually approximately 1 week, to observe for idiosyncratic reaction or other untoward side effects.

STRUCTURAL HEART DISEASE: VALVULAR AND CONGENITAL

The detection of significant structural heart disease in trained aircrew, either valvular or congenital, commonly leads to assignment of an operational flying restriction with a requirement for regular cardiac assessment for any change or progression. In some cases, it leads to permanent grounding. Aeromedical concerns with respect to structural heart disease include the potential for sudden incapacitation due to arrhythmias, thromboembolic events, or other complications such as subacute bacterial endocarditis (SBE). For many years, the American Heart Association has published guidelines for SBE prophylaxis in cooperation with appropriate professional societies from the dental, infectious diseases, and pediatric communities.

In early 2007, the American Heart Association published new SBE guidelines that are dramatically different from past recommendations. SBE prophylaxis was recommended only for specified high-risk groups, particularly for dental procedures, respiratory tract procedures, and procedures on infected skin, skin structures, or musculoskeletal tissue. Prophylaxis was no longer recommended for gastrointestinal or genitourinary procedures. Conditions commonly seen by most aerospace medicine practitioners were not included in the list of high-risk conditions. Such common conditions no longer recommended for SBE prophylaxis included, but are not limited to, mitral valve prolapse (MVP), bicuspid aortic valve (BAV), mitral or aortic regurgitation with normal valve, and uncorrected small defects of the atrial and ventricular septum. The high-risk group was limited to prosthetic cardiac valves, previous SBE, select congenital heart conditions, and cardiac transplant patients with valvulopathy. As the medical community reacts and responds to these very significant changes, aerospace medicine practitioners, licensing authorities, and aircrew standards groups are advised to consult their own cardiology and infectious disease consultants for specific occupational guidance.

Additional operational concerns include impairment of cardiac output under high $+G_z$ with loss of consciousness, worsening of the valvular problem through repetitive $+G_z$ exposure, or the hypothetical potential for type II decompression sickness (DCS) through right-to-left shunts. Developments in operative and percutaneous treatments of structural heart disease have raised further operational concerns over the suitability and durability of these repairs in the hostile aviation environment. This has resulted in additional challenges for aviators with repaired structural heart disease as well as the organizations and aeromedical physicians who are charged with their care.

Echocardiographic Screening in Aircrew

For military and other flying training programs, screening for structural cardiac disease may reduce the problem of congenital and acquired valvular heart disease in trained aircrew. Over the last decade, some air forces have incorporated echocardiographic screening into their aircrew medical selection programs (30). Echocardiographic screening programs for aircrew applicants are ideally managed by providing centralized screening at a single or at most a very limited number of locations, supervised by a cardiologist knowledgeable about the aeromedical implications of structural cardiac anomalies. Application of high-quality echocardiographic techniques by certified, well-trained technicians, with consistent interpretation using well-defined criteria such as those of the American Society for Echocardiography is most important. Screening echocardiography can detect structural heart disease including valvular disorders and congenital heart disease, as well as disorders of the myocardium such as cardiomyopathies or segmental wall motion abnormalities.

Utilizing screening echocardiography, the incidence of disqualifying findings in candidates was found to be 7.8% in Canadian Forces aircrew (31). The most common disqualifying echocardiographic finding was MVP (4.5%), followed by aortic regurgitation through normal valves (1.3%) and BAV with or without regurgitation (0.9%). Later studies in USAF pilot candidates revealed a disqualification rate of only 1.5% (1), the difference mainly reflecting a lower incidence of MVP as a result of more stringent criteria for echocardiographic diagnosis of MVP. A review of 299 Canadian Forces pilot candidates screened in 1999 and 2000 showed a disqualification rate of 2.6% for echocardiographic findings, with an incidence of MVP of only 1.3% (Gray GW, 2006).

Recent investigations into the utility of echocardiographic screening programs have called into question their overall effectiveness. In an analysis of 20,208 USAF pilot applicants, the initial disqualification rate was 1.45% ($n = 294$). The most common abnormalities were BAV with or without mild aortic insufficiency (AI) (0.76%), mild AI with a trileaflet aortic valve (0.25%), and MVP (0.29%). Over a 12-year period of data collection, however, waiver standards were gradually changed so that the earlier diagnoses, while still disqualifying, were "waiverable" for entry into pilot training. Therefore, after applying current waiver standards to the entire cohort, it was found that only nine screening examinations yielded a diagnosis which was disqualifying and ineligible for waiver, a rate of only 0.045% (32). The utility of echocardiography screening is therefore seen to be tied to aeromedical waiver policy, and should be tailored by each aircrew training organization appropriately.

Echocardiography can also play an important role in the evaluation of trained aircrew with valvular heart disease for determining medical fitness for continued flying status or licensing medical certification. Echocardiography has been effectively utilized to assess the question as to whether repeated exposure to sustained G-forces has an effect on cardiac structure or function. In a multinational study of North Atlantic Treaty Organization (NATO) military aircrew, which compared echocardiographic findings in 289 experienced and actively flying high-performance pilots with 254 pilots of non–high-performance aircraft, there were no significant differences found in cardiac structure or function (33).

Clinical Examination for Structural Heart Disease

Particular attention should be paid to the cardiac examination in both trained aircrew and aircrew candidates, in whom clinical signs of congenital and early-acquired valvular disease may be very subtle. Murmurs and extra sounds may vary considerably with end-diastolic volumes and may be heard in one position but not another. Physicians examining aircrew should incorporate into their physical examination a routine of cardiac auscultation designed to elicit signs of structural heart disease. Auscultation should be done in a series of positions beginning with the individual seated, progressing to supine, then in the left lateral decubitus position, and then standing. This should be followed by auscultation in the crouch or squat position, followed by standing. Finally, if any suspicious findings are elicited, further auscultation may be done through and after a Valsalva maneuver, with dynamic exercise such as handgrip, or after inhalation of amyl nitrite. By incorporating such a protocol into the clinical examination routine, physicians will maximize the sensitivity of the physical examination for detecting structural cardiac disease.

In the generally healthy and fit aircrew population, physiologic flow murmurs are common, and are characterized by their generally soft quality (grade 1-2 out of 6), and midsystolic timing. Such innocent flow murmurs generally disappear on standing. Right-sided murmurs generally increase with inspiration and left-sided murmurs with expiration. Typical systolic physiologic flow murmurs do not require further assessment. The following auscultatory findings should be considered sufficient indication for echocardiographic assessment: new murmur, prominent midsystolic murmurs, grade 3 or greater; holosystolic and mid-through-late systolic murmurs; systolic murmurs which increase on standing, or after Valsalva; and all diastolic murmurs. The finding of extra cardiac sounds such as an ejection click, apical nonejection click, or fixed split second sound should also trigger an echocardiographic examination for an underlying structural heart substrate.

VALVULAR HEART DISEASE

Aortic Stenosis

Valvular aortic stenosis (AS) occurs as a consequence of a congenital BAV, rheumatic fever, or as a result of degenerative valve disease. The latter occurs in older adults and is unlikely to be an aeromedical issue. Although not unknown, rheumatic heart disease is uncommon in industrialized countries, so the most common substrate for aortic stenosis in aviators is a BAV.

Valvular AS is suspected clinically by the presence of a crescendo–decrescendo systolic murmur heard in the upper right sternal area, with radiation to the carotids and down the left sternal border to the cardiac apex, where it may be best heard. Severe AS may not produce appreciable murmurs, but at that stage clinical symptoms are generally established. There may be an ejection systolic click, and a fourth heart sound reflecting developing LVH. The ECG may show evidence of LVH and strain, and the chest x-ray may show cardiac enlargement with left ventricular prominence.

Regardless of etiology, the natural history of AS is one of gradual progression over years, during which the individual is asymptomatic. The outflow obstruction caused by valvular AS results in left ventricular pressure overload and consequent hypertrophy. With progression of AS, the pressure overload leads to left ventricular diastolic and later systolic dysfunction with left ventricular dilatation. The onset of symptoms, which include dyspnea, angina, and syncope, indicates progression to moderate or severe stenosis with significant potential for acute incapacitation.

From an aeromedical standpoint, AS should be detected well before the onset of symptoms through clinical and ECG findings on periodic medical examinations. A two-dimensional (2-D) echocardiogram and Doppler study will elucidate aortic valve morphology and left ventricular size, wall thickness, and function. Occasionally, cardiac catheterization may be necessary if the echocardiographic study is inadequate or concurrent definition of the coronary arteries is required.

The prognosis and hence the aeromedical disposition depends on the degree of stenosis, which is classified as *mild, moderate,* or *severe*. Classification systems have been developed based on valve area, pressure gradient, and maximum flow velocity. Using valve area, published guidelines grade aortic stenosis as mild with valve area greater than 1.5 cm^2, moderate for valve areas 1.1 to 1.5 cm^2, and severe when the valve area is less than or equal to 1.0 cm^2. Using mean pressure gradient, stenosis is graded as mild for mean gradients less than or equal to 20 mm Hg, moderate for gradients 21 to 39 mm Hg, and severe for gradients greater than or equal to 40 mm Hg. Maximum flow velocity is a newer parameter with less data available related to outcome.

On the basis of mean pressure gradient, athletes with mild AS are considered fit for all competitive activities. For mild-to-moderate AS, competition is restricted to low-to-moderate intensity isometric and aerobic activities. Individuals with severe AS or moderate AS with symptoms are advised against participation in all competitive sports.

Suggested aeromedical recommendations combine valve area and mean pressure gradient, as shown in Table 13-2. The aeromedical concerns for AS relate to the occurrence of clinical events (syncope, angina, and sudden death), and the limitation of cardiac output through the fixed obstruction, a significant concern for aerobatic and military high-performance flying.

Aircrew with mild AS are considered fit for unrestricted flying but require periodic echocardiographic follow-up. Actual experience with mild AS and high-performance flight is scant and as yet unreported. Mild AS may progress or may remain static for many years. For aeromedical purposes, assessment of the rate of progression requires an annual echocardiogram for at least several years to assess serial change in the severity of stenosis and left ventricular parameters. Fortunately, up to half the number of individuals with mild AS may remain stable over many years and in such cases the periodicity of serial echocardiography may be extended to biannual. The average rate of progression is approximately 0.12 cm^2/yr, but unfortunately it is not possible to predict the rate of progression in any particular individual.

TABLE 13-2

Classification of Aortic Stenosis

Grade of Aortic Stenosis	*Valve Area (cm^2)*	*Mean Gradient (mm Hg)*
Mild	>1.5	≤ 20
Mild-to-moderate	1.1–1.5	≤ 20
Moderate	1.1–1.5	21–39
Severe	≤ 1.0	≥ 40

The event rate increases as stenosis progresses from mild to moderate. Asymptomatic moderate AS has an event rate of approximately 5% per year. If symptoms are present, the event rate is at least 10% per year. Therefore, individuals with moderate AS are unfit for military flying duties. For mild-to-moderate asymptomatic AS, consideration may be given to restricted low-performance flying operations. Patients with severe AS are candidates for valve replacement and are unfit for military flying. Although the incidence of sudden death, even with severe AS, is likely less than 1% per year, licensing agencies considering medical certification of aviators with moderate or severe AS should consider the potential for other events, including angina and syncope, which may occur in emergency situations with high levels of adrenergic stimulation. Carefully supervised exercise or pharmacologic (e.g., dobutamine) stress testing may help identify individuals with stress-induced symptoms despite a negative medical history, or conversely, patients with a low cardiac output and only mild-to-moderate AS.

Aortic Regurgitation

Aortic regurgitation (AR) develops as a result of aortic valve disease, either idiopathic or secondary to BAV, rheumatic heart disease, endocarditis, or degenerative disease with sclerosis and calcification of the valve. It may also develop as a result of aortic root dilatation related to hypertension, aortitis, or connective tissue disease. In the aircrew population, BAV and idiopathic regurgitation through a trileaflet valve are most common.

The hemodynamic effects of chronic AR are due to volume overload, with gradual enlargement and hypertrophy of the left ventricle. Symptoms develop only late in the process as left ventricular systolic function declines and left ventricular failure develops. Initial symptoms are unexpected shortness of breath on exertion, reduced exercise tolerance, and general fatigue, and later, as left ventricular failure ensues, orthopnea and paroxysmal nocturnal dyspnea. Angina may develop in the absence of coronary disease due to hypertrophy-driven increased oxygen demand with reduced coronary perfusion.

Rarely, acute AR may develop as a result of endocarditis or aortic dissection. Such a sudden volume overload may be poorly tolerated with resultant pulmonary congestion and edema, and low-flow state with shock and sudden death possible outcomes. This is a medical and surgical emergency.

The classical clinical finding in AR is a high-pitched decrescendo diastolic murmur heard along the sternal border (left side for aortic valve disease, right side for aortic root disease). This murmur is easily missed, especially with mild AR. Often more prominent is a short ejection systolic murmur radiating up the carotids from flow turbulence due to the increased stroke volume. Auscultation of such a systolic murmur should prompt careful examination for an AR diastolic murmur, which may be enhanced by listening with a breath-hold at end-expiration in the seated position with the individual leaning forward or during a squat. When the AR jet is directed across the anterior mitral valve leaflet thereby preventing full opening, auscultation may reveal a rumbling diastolic murmur at the apex due to functional mitral stenosis (Austin-Flint murmur). Other clinical signs include awide pulse pressure, and rapid decay of the pulse pressure.

The diagnosis and quantification of severity are best assessed through echocardiography and Doppler studies. The 2-D echocardiogram will provide information on left ventricular size and function. AR is graded as trace, mild, moderate, or severe based on several qualitative and semiquantitative measures on color flow imaging, Doppler-derived pressure decay half-times, and flow reversal in the descending thoracic aorta. Pressure halftimes greater than 600 m/s are consistent with trace or mild AR, 500 to 600 m/s with mild AR, 200 to 500 m/s with moderate AR, and less than 200 m/s with severe AR. Other investigations used to quantify the severity and hemodynamic consequences of chronic AR include aortography, rest and exercise radionuclide ventriculography, and magnetic resonance imaging (MRI).

As left ventricular volume increases, treatment with vasodilators, such as hydralazine and nifedipine, have been shown to delay the requirement for valve replacement and improve operative results, and are currently recommended therapy for even asymptomatic patients with severe AR and left ventricular dilatation. ACE inhibitors have similar hemodynamic effects and are more often prescribed, although results of the outcomes are not as well demonstrated. Valve replacement is indicated as symptoms worsen, or in asymptomatic individuals with failing left ventricular systolic function (ejection fractions $<25\%$) or severe dilatation (end-systolic or end-diastolic dimension >55 or 75 mm, respectively).

From an aeromedical standpoint, chronic AR is unlikely to cause acute incapacitation, and aeromedical concerns relate to issues of selection into flying training, medications used to treat AR in later stages, and possible aggravation of AR by stresses encountered in high-performance flying.

With regard to selection, individuals with moderate or severe AR are likely to progress to require valve replacement and are not good candidates for entry into flying training, especially military. While slight or even mild regurgitation through the mitral, tricuspid, and pulmonic valves is not an uncommon finding on routine screening echocardiograms, trace AR is a rarer finding, and mild AR is very uncommon. An analysis of 52 military aviators with BAV and mild AR revealed that only 15% progressed to moderate AR over a 3.5 year follow-up (mean age at baseline 47 years, follow-up range 0.5 to 14.5 years) (34). Therefore, the available information suggests that mild or less AR is unlikely to progress, and therefore may be acceptable for selection into military pilot training. However, variability in valve morphology (tricuspid versus bicuspid, degree of thickening and/or calcification) may accelerate or slow AR progression compared to published rates. Individuals with these findings may present an increased risk for training investment resources (1).

The possible hemodynamic effects on AR of repeated exposure to radial accelerative forces and countermeasures are unknown, but the repetitive cycling of preload and afterload could theoretically aggravate both aortic root dilatation and aortic regurgitation. The echocardiographic study, which addressed the question of possible adverse cardiac effects of repeated exposure to high sustained $+G_z$ in NATO aircrew, found no cases of AR in the cohort of 289 high-performance pilots, while four cases were noted in the control group of 254 non–high-performance pilots (33). A small USAF study followed 16 high-performance pilots and a control group of 16 low-performance pilots for a mean of 5 years. Severity of AR increased in five low-performance pilots but in only one high-performance pilot, and left ventricular function and dimensions remained stable in both groups (1).

Current aeromedical recommendations are that individuals with mild AR are fit for unrestricted flying duties. Aircrew with moderate AR should be restricted from high-performance aircraft. Aviators with severe AR and normal LV dimensions and systolic function may likewise be fit for low-performance restricted flying, but as LV dilatation occurs such individuals should receive vasodilator therapy as standard of care and may then be considered unfit for military flying duties. Alternatively, because sudden events are not an issue, severe AI might be considered acceptable for continued low-performance flying until the aviator meets published guidelines criteria for valve surgery. The decision as to civilian medical certification and licensing will depend on the policy of the licensing agency regarding vasodilator therapy. All aircrew with AR beyond trace should be followed up with echocardiographic and Doppler study at 1- to 3-year intervals.

Mitral Regurgitation

Mitral regurgitation (MR) can develop due to abnormalities in the mitral leaflets or supporting structures including the annulus, chordae tendineae, and papillary muscles. Rupture of a major chorda tendinea or papillary muscle most commonly occurs in the setting of ischemic heart disease and causes acute, often severe MR. This is a medical emergency with sudden rise in left atrial and pulmonary vascular pressures leading to pulmonary congestion and edema and often atrial fibrillation.

The most common cause of progression of chronic MR to moderate or severe degrees is myxomatous mitral valve disease with MVP. Other causes include dilated cardiomyopathy, endocarditis, and rheumatic heart disease. Chronic MR causes volume overload of the left ventricle, which dilates to maintain stroke volume. Left atrial enlargement develops to compensate for increased volume and pressure. Eventually, progressive left ventricular dilatation leads to contractile impairment and heart failure. Atrial fibrillation may develop with progressive left atrial enlargement, predisposing to thromboembolic events.

Early symptoms of MR include easy fatigability and unexpected dyspnea on exertion. Progression leads to heart failure symptoms with orthopnea, paroxysmal nocturnal dyspnea, and edema. Physical findings are an apical systolic murmur radiating laterally to the axilla. Posteriorly directed jets may be heard over the back. With myxomatous disease, a variable midsystolic click of MVP may be heard preceding the murmur. As MR progresses in severity, the duration of the murmur may extend through systole. Paradoxically, severe MR may have little to no murmur, even on careful auscultation. In late stages of disease, the first heart sound may be muffled, and a third heart sound often develops.

Repetitive exposure to high sustained $+G_z$ with related protective countermeasures that increase afterload might be expected to aggravate the severity of MR, but there is little data to address this concern. The NATO aircrew echocardiographic study (33), which addressed the question of possible adverse cardiac effects of repeated exposure to high sustained $+G_z$, found no cases of abnormal (as opposed to physiologic) MR. Albery (35) reported no change in MR in 18 centrifuge subjects each exposed to more than 45 minutes of cumulative $+G_z$ exposure greater than or equal to 2 G. Although MR was not specifically monitored, a longitudinal study of six female centrifuge subjects showed no change in left atrial dimension after approximately 100 exposures of 3 minutes to high $+G_z$ (up to 9 G) over 7 months. This is considered to be approximately equivalent to a 3-year G-dose in typical F-16 pilots (36).

Aeromedical disposition of MR must take into consideration both the underlying cause and hemodynamic effects. Evaluation should include an echocardiographic and Doppler study to assess the degree of regurgitation as well as cardiac structure and function. Transesophageal echocardiography (TEE) provides a sensitive assessment for MR and may be required for individuals with technically unsatisfactory transthoracic echocardiograms. Exercise stress testing will provide information on exercise tolerance and helps assess for exercise-induced arrhythmias. Stress echocardiography or exercise radionuclide ventriculography may be helpful to assess the left ventricular response to exercise.

Trace or even mild MR is a common finding on routine echocardiographic Doppler studies in aircrew candidates (1,31). In the presence of a structurally normal heart, including the mitral valve apparatus, this is considered to be a physiologically normal variant. The available evidence suggests that physiologic MR is not aggravated by even high-performance flying, and such individuals are fit for training and unrestricted flying and licensing.

Progressive MR leading to moderate-to-severe and severe regurgitation is an abnormal finding. While G-exposure apparently does not affect physiologic MR, there is no data available on moderate or severe MR and such individuals may be restricted from high-performance flying, particularly when there is evidence of chamber dilatation or left ventricular dysfunction. Continued non–high-performance flying and civilian licensing are reasonable with annual review, provided there are no symptoms, sinus rhythm is maintained, the left atrium is not markedly enlarged (<50 mm) and left ventricular function is normal or near normal.

Mitral Stenosis

Mitral stenosis is most commonly acquired as result of rheumatic fever or as a complication of systemic lupus erythematodes. It may remain asymptomatic for many years, and may be discovered in candidates for training or licensing with an unknown or undisclosed rheumatic fever history—only approximately 50% of patients with isolated mitral stenosis recall a history of rheumatic fever. Careful clinical examination should detect the characteristic opening snap and low-pitched diastolic rumble heard best with auscultation in the left lateral decubitus position at the apex with the bell of the stethoscope. The first sound may be accentuated. ECG may show evidence of left atrial enlargement, with biphasic P waves in V1 being the earliest sign, and widened, notched inferior P waves evolving as enlargement progresses. The chest x-ray may show left atrial enlargement, pulmonary congestion, and mitral calcification.

Mitral stenosis restricts transmitral forward diastolic flow, which is maintained by elevating left atrial pressure, leading to progressive left atrial enlargement. Symptoms typically develop in the third and fourth decade as forward flow is progressively restricted and pulmonary venous and capillary pressures rise, with unexpected dyspnea on exertion and easy fatigability as the earliest symptoms. Left atrial enlargement predisposes to atrial fibrillation, which occurs in 30% to 40% of patients with symptomatic mitral stenosis.

Doppler echocardiography is the test of choice to establish the diagnosis and assess the severity of mitral stenosis. Valve morphology and planimetered opening valve area, left atrial and ventricular dimensions, and left ventricular function are assessed on the 2-D study. And, valve area can be further calculated by measuring the pressure gradient with Doppler.

Interventions to relieve mitral stenosis include percutaneous balloon valvuloplasty, surgical commissurotomy, and valve replacement. Balloon valvuloplasty is the initial intervention of choice. For patients not suitable for valvuloplasty, such as with significant concurrent MR, surgical commissurotomy provides equivalent short- and medium-term results. Both procedures are palliative, though, with stenosis gradually recurring, and approximately 5% to 10% of patients requiring a repeat procedure within 5 years.

Rheumatic mitral stenosis is a progressive disease and is disqualifying for candidates for military aviator training. Applicants for civilian licensing require careful assessment but may be suitable provided the individual is asymptomatic and the degree of stenosis is mild (valve area $>2.5\ cm^2$), sinus rhythm is maintained, left ventricular function is normal, and the left atrium is not markedly enlarged (<50 mm).

Tricuspid Valve Disease

Trace and mild tricuspid regurgitation are very common findings, detected on more than half of screening echocardiograms in military pilot candidates (1,31). Even moderate tricuspid regurgitation is not unusual, and should be considered physiologic and not a disqualification for aircrew selection or training, in the absence of secondary causes. Isolated severe tricuspid regurgitation is rare, but may be caused by rheumatic disease, tricuspid valve prolapse, endocarditis, trauma, carcinoid, or secondary to right ventricular dilatation due to pulmonary or cardiac causes. The clinical findings are a long or pansystolic murmur at the lower left or right sternal border that increases with inspiration. Prominent V waves are typically observed in the jugular venous pulse, and in severe cases, pulsatile hepatomegaly.

Echocardiography confirms the diagnosis and assesses the severity and cause. Aeromedical disposition will depend on the underlying cause as well as the severity of regurgitation. Isolated moderate-to-severe or severe regurgitation, for example due to trauma or prolapse, with normal right ventricular function may be suitable for low-performance restricted military flying or civilian licensing with regular periodic echocardiographic and clinical assessment.

Tricuspid stenosis occurs in 5% to 10% of patients with rheumatic mitral stenosis. The rheumatic tricuspid valve is usually both stenotic and regurgitant. The involvement of multiple cardiac valves is a disqualification for military aviator selection and would likely be for commercial civilian licensing.

Pulmonary Valve Disorders

Right ventricular outflow obstruction can be infundibular, supravalvular, or due to valvular pulmonic stenosis (PS). Infundibular stenosis is almost always associated with a ventricular septal defect. Valvular PS is generally congenital and mild in severity when diagnosed in adults. The characteristic physical finding is a systolic crescendo–decrescendo murmur heard best along the left upper sternal border, accentuated by inspiration, which radiates to the left infraclavicular area. There may be an ejection click, which is better heard during expiration. The diagnosis is confirmed by echocardiography, which shows a conical or dome-like fusion of the pulmonary valve cusps. In most cases, the severity can be graded by Doppler flow assessment of velocities, although occasionally right heart catheterization may be necessary. Mild PS (peak gradient <30 mm Hg) generally carries a good prognosis and such individuals are considered medically fit for military aviator selection and training, and for civilian licensing, with periodic assessment for the unusual situation of progression. Moderate or severe PS results in right ventricular hypertrophy and is more likely to be progressive, resulting in symptoms such as undue exertional dyspnea due to limitation of cardiac output. Moderate to severe PS is treated with balloon valvulotomy with good long-term outcomes. Individuals with moderate or severe PS are unfit for military aircrew selection, but may be fit for civilian licensing if asymptomatic, with good exercise tolerance on exercise stress testing. Aviators who are postvalvulotomy may be acceptable for continued civilian licensing or military flying duties, provided there is a good hemodynamic result and no significant residua or complications.

Trace and mild degrees of pulmonary regurgitation (PR) are common findings on screening echocardiograms and may be viewed as physiologic normal variants. Progression is rare and such individuals are considered medically fit for military aircrew selection and civilian licensing. Moderate and severe PR are rare but require case-by-case judgment for aeromedical disposition, based on the severity of PR, symptoms, and hemodynamic effects such as right ventricular dilation and tricuspid regurgitation.

Valve Replacement or Repair

Valve replacement or repair may be required for progressive or acute regurgitation, endocarditis, or stenosis, generally involving the aortic or mitral valves. Criteria for valve replacement and management of such patients have been well established. Although improving hemodynamics, valvular surgery carries the potential for long-term complications with event rates often unacceptable for continued flying. Replacement valves may be mechanical or bioprosthetic, either heterografts (xenografts) derived from animal tissue (bovine, porcine) or homografts derived from human sources. Complications include gradual or sudden valve failure requiring reoperation, endocarditis, thrombosis, thromboembolism, and arrhythmias. Mechanical valves require life-long warfarin anticoagulation with attendant risk of significant bleeding, which must be factored into the risk assessment for aeromedical disposition. The event rate for complications related to mechanical valves and required anticoagulation may exceed 5% per year and is generally not compatible with continued flying status (37). Heterograft valves do not require anticoagulation, but are more likely to gradually deteriorate and to require replacement. The overall complication rate for standard bioprosthetic valves also exceeds 5% per year (38). Mechanical and heterograft bioprosthetic valves are considered disqualifying for military flying, and with complication rates exceeding 5% per year, do not meet the generally accepted 1% rule for commercial licensing. Newer stentless bioprosthetic valves have improved hemodynamics, although the thromboembolism rate remains approximately 1% per year, and valve degeneration requiring replacement is approximately 2% per year.

More promising from an aeromedical standpoint are human homograft valve replacements. These procedures involve placement of an allograft valve, which is antibiotic-sterilized and preserved by cryotherapy. The Ross procedure involves replacement of a diseased aortic valve with a pulmonary autograft, the pulmonic valve then being replaced by an aortic allograft. For younger patients, autografts tend to have a better long-term survival. As for other bioprosthetic valves anticoagulation is not required. The long-term outcome is generally better for homografts than heterografts, although the incidence for both valve-related complications is approximately 2% to 4% per year. However, aeromedically worrisome complications such as acute valve failure are extremely rare, and in selected patients with excellent surgical outcomes and a return to normal or near normal hemodynamics, consideration may be given to flying duties in multicrew operations.

The USAF currently has five aviators with replaced aortic valves on flight duties, nearly all with aortic homografts (Strader, JR, 2007). All but one have been restricted to multipilot, low-performance operations. Recently, however, the USAF returned to unrestricted flying duties—the first high- performance pilot with an aortic valve replacement (39). In this case, a novel porcine "whole root" heterograft was used, which restored normal hemodynamics of the left ventricular outflow tract, aortic valve, and aortic root as a whole (40). These types of investigational approaches to aortic valve replacement are promising from an aeromedical viewpoint, in that they appear to preserve normal hemodynamics with reasonable durability and low-event rates. As with all aviators with valve surgery, however, these must be evaluated on a case-by-case basis.

Mitral valve replacement carries complication rates similar to that for aortic valve replacement. The need for anticoagulation is even greater with mechanical and bioprosthetic mitral valve replacement due to lower flow rates across the valve and an increased likelihood for thrombus formation. Therefore, mitral valve replacement generally necessitates warfarin anticoagulation and in general is a contradiction to aviation duties. However, surgical repair rather than replacement of regurgitant mitral valves has resulted in lower postoperative complication rates and improved long-term prognosis. Repairs of degenerative, myxomatous, or flail mitral valve leaflets usually involve resection of the diseased leaflet with surgical repair of the remaining sections. Mitral valve repairs may often be combined with ring annuloplasty to attempt to normalize mitral annular geometry and reapproximate the mitral leaflet cusps, particularly if the preoperative condition was associated with severe MR. With an excellent surgical outcome, improvement in hemodynamics, normal or near-normal valve and myocardial function, maintenance of sinus rhythm, and good exercise tolerance, consideration may be given to a return to restricted multicrew operations after mitral valve repair. The USAF currently has eight aircrew with repaired mitral valves on restricted flight duties (Kruyer, WB, 2007).

When an aviator is faced with the need for valve surgery, knowledge of the restrictions and associated risks and benefits of the various surgical options can assist in medical decision making. Therefore, close collaboration between the surgical consultant, aviator, and aerospace medicine specialist is recommended. Most aviators choose to avoid valve replacements requiring Coumadin if possible, due to the associated event rates and aviation restrictions inherent with mechanical valves. Counseling on the expected outcomes of alternative valve replacements (e.g., aortic homografts) or repairs (e.g., mitral) and rates of long-term complications such as the risk for eventual reoperation is crucial before any operative decision.

Aeromedical management of aviators who are on any type of flight duties with repaired or replaced cardiac valves requires serial studies to assess for continued competence of the surgical repair and lack of associated complications. This can largely be achieved with serial echocardiography to assess for valve function, continued anatomic alignment, left ventricular function, valvular hemodynamics, and degree of residual regurgitation or stenosis, if any. Stress echocardiography can be useful to assess valve function under physiological stress, and can be achieved with either exercise (treadmill or supine bicycle ergometry) or pharmacologically (dobutamine infusion). For aviators with aortic valve replacements, it is important to know if the coronary arteries were reimplanted along with the valve replacement, as this would necessitate periodic screening for coronary artery stenosis at the reanastomosis. Finally, incorporating 24-hour ambulatory ECG monitoring into a periodic evaluation allows for assessment of any associated arrhythmias, although the appearance of valve surgery–related arrhythmias late after operative repair is rare.

CONGENITAL HEART DISEASE

Congenital heart disease may present aeromedically in candidates or license applicants with known repaired congenital defects, with undiagnosed defects detected clinically or on echocardiographic screening, or in aircrew following training or licensing.

Bicuspid Aortic Valve

BAV is the second most common form of adult hereditocongenital heart disease after MVP. The incidence in the adult population based on necropsy studies is 1% to 2% (41), but on screening echocardiograms in aircrew candidates, the incidence was found to be only 0.5% to 0.9% (1,31). The lower incidence in military pilot candidates may represent a selection bias because applicants must first pass screening medical examinations.

Clinically, BAV may be suspected by the presence of systolic ejection clicks. These are high-pitched sounds occurring concurrent with or immediately following the first heart sound and are best heard with the diaphragm in the aortic area just to the right of the upper sternum or at the apex. There may be an associated aortic outflow murmur due to flow turbulence without stenosis, or murmurs related to aortic stenosis or regurgitation, which occur as complications. Auscultatory findings in BAV are not consistent, and in many individuals BAV is asymptomatic and clinically silent before the onset of complications. 2-D echocardiography provides a sensitive and specific tool for diagnosis of BAV and for serial follow-up for developing complications.

Complications of BAV include endocarditis, aortic stenosis, aortic regurgitation, and ascending aortic aneurysm formation with or without aortic dissection. Most of the available natural history data is based on necropsy studies with attendant selection bias, with a paucity of data based on echocardiographically diagnosed, normally functioning BAVs. Complications of BAV are age related, with endocarditis and critical aortic stenosis most common in childhood and early adult life, then aortic regurgitation and aortic dissection more common in early to middle adult age.

The BAV is a substrate for endocarditis with estimates as high as 30% based on selected case series, although the true incidence is likely much less (41). BAV incurs about a ninefold increase in the relative risk of aortic dissection, which is usually preceded by aortic root dilatation, often associated with hypertension. Aortic root enlargement is a common finding in BAVs, and occurs as often in normally functional BAVs as in those complicated by stenosis or insufficiency. With the decline in rheumatic fever, BAV is the most common substrate for development of aortic stenosis, which tends to develop slowly and progressively over time with the development of sclerosis in the second and third decade and calcification thereafter. The average aortic valve gradient increases concurrently by 18 mm Hg per decade. Aortic regurgitation in BAVs may occur in isolation, or as a consequence of endocarditis or aortic root dilatation. Conversely, aortic regurgitation may cause aortic root dilatation. Aortic regurgitation tends to occur at a younger age than aortic stenosis, affecting aircrew during their flying career.

From an aeromedical standpoint, BAV is primarily of concern because of the potential for complications. Over a lifetime, serious complications occur in at least one third of individuals born with BAV (41). Of these complications, only aortic dissection is likely to present as sudden incapacitation, although aortic regurgitation may develop suddenly in an infected valve. In an analysis of 52 active duty USAF aviators with BAV (mean age 47 years), baseline trace or mild AI and AS were common (60% to 70% of the cohort). Over an average of 3.5 years of follow-up, progression to mild or moderate AR or AS was relatively common, occurring in more than half the subjects. However, progression to severe disease was rare (34). Therefore, while it is true that many individuals with BAV ultimately progress to requiring surgical intervention, most of these will not happen until after a military aviation career is complete. This may be a larger issue for civilian aviation authorities because age restrictions on civilian licensing would allow continued duties for many of the individuals who will ultimately progress to needing medical or surgical intervention.

From a licensing or retention standpoint, individuals with normally functioning BAVs are fit for unrestricted flying. Annual clinical assessment and periodic echocardiographic follow-up (e.g., every 2 to 3 years) should be performed to assess for developing complications. It is a risk assessment decision whether or not to admit into military flying training applicants with BAV. Most such individuals are likely to be able to complete their projected career, but a policy decision that admits individuals with BAV must accept a degree of attrition of trained aircrew due to later complications. Aircrew admitted into training with BAV will require periodic echocardiography to assess for developing complications, and will require antibiotic prophylaxis for dental and surgical procedures. The impact of the stresses of military flying such as G-forces and G-protection life support equipment and maneuvers on the progression of BAV complications such as aortic root dilation, dissection, and aortic regurgitation is unknown. A recent publication, however, found that repeated exposure to $+G_z$ stress over a follow-up of 12 years in high-performance pilots did not accelerate progression of BAV compared to low-performance pilots, suggesting that the presence of a BAV in and of itself should not be automatically disqualifying for aviator duties (42).

Mitral Valve Prolapse

MVP occurs when the leaflets of the mitral valve extend beyond the plane of mitral annulus into the left atrial cavity during ventricular systole. This is a common congenital valvular abnormality, with prevalence in the general population of 2% to 4% (1,24). The prevalence of MVP in most aviation cohorts has been reported as ranging from 0.2 to 1.0% (1,32), probably reflecting a selection bias due to flight-commissioning physicals. The diagnosis of MVP is usually made on 2-D echocardiography and the definition has been standardized to require prolapse of at least 2 mm beyond the annular plane in the parasternal long-axis view. M-mode findings or displacement of the posterior leaflets on apical views may provide supportive evidence. MVP may be suspected clinically when a midsystolic click is heard on auscultation. The click varies in timing with changes in left ventricular volume, moving later in systole as volume increases. Therefore, a true midsystolic click can be differentiated from other sounds by maneuvers on physical examination designed to alter left ventricular volume conditions (squat, Valsalva strain, and release phase). A brief late systolic murmur often, but not always, follows the midsystolic click. These auscultatory findings may be transient and dissimilar on different days, reflecting differing autonomic tone, hydration, volume status, and other factors.

Morphologically, MVP is often associated with other structural abnormalities of the mitral chordae and subvalvular apparatus. There are commonly histological abnormalities of the collagen matrix of the leaflets themselves, which predispose over time to the development of mitral leaflet thickening and myxomatous degeneration due to glycoprotein deposition, usually at sites of chordal insertion. The chordae undergo similar destructive changes with elongation and thinning (the anatomic substrate for chordal rupture). The posterior leaflet is most often involved (67%), with isolated involvement of the anterior leaflet infrequent (10%), and both in approximately 25%.

The major functional concern arising from MVP is the degree of any associated MR. As the valve deteriorates over time, MR may progress from being absent or only trivial early in the disease to severe MR requiring surgical correction. In the late stages, a sudden increase in the degree of MR may occur as diseased chordae may rupture and flail leaflets result. Although the timeline for progression of disease typically is in decades, young flight crew and pilot applicants with MVP and any degree of MR pose operational and selection questions to most aviation organizations and authorities regarding the risk for progression to severe disease. Additional concerns with MVP include the risk of infective endocarditis (IE), which appears to be related to the degree of structural valve abnormality. The presence of a click alone confers no increased risk for IE. However, the incidence of IE has been as high as 6% to 8% in patients with MVP and regurgitant murmurs. In case-controlled studies, the overall relative risk is approximately five times normal (43). The current consensus recommendation from the American Heart Association for endocarditis prophylaxis is that antibiotics are not recommended for most individuals with MVP.

Cerebral transient ischemic attacks and stroke have been attributed to MVP. There are multiple confounding factors, however, including prothrombotic coagulation disorders, other cardiac substrates such as patent foramen ovale (PFO), atrial septal defect (ASD), or left atrial enlargement with atrial fibrillation. However, both the absolute and relative attributable risks are extremely low, and in persons younger than 45 years, the Framingham investigators found no evidence linking MVP with stroke (1).

Although the absolute risk for clinical complications is low, because of the increased relative risk for complications including endocarditis, thromboembolic events, progressive MR, and arrhythmias, particularly in the high sustained $+G_Z$ environment, MVP has been considered disqualifying for selection in pilot training by most NATO air forces (30). The USAF policy regarding MVP changed in 2004, when pilot applicants with MVP and mild or less associated MR were allowed waivers for initial pilot training. When discovered in a trained aircrew, the policy is generally to allow continuation of flying duties, including high performance flying, but with regular surveillance for complications. This should include an echocardiographic/Doppler study, treadmill test, and 24-hour ambulatory ECG monitoring. For duties involving high sustained $+G_z$, a monitored centrifuge evaluation for arrhythmias may be considered; however, this was found to be unproductive in a review of approximately 400 USAF aviators with MVP. While potentially incapacitating endpoints occur infrequently when MVP is discovered in trained aircrew, the overall rate of disqualifying endpoints was found to be 1.4% per year in a retrospective study of USAF aircrew (1).

Defects of the Atrial Septum

Defects in interatrial septal development may result in an ASD, atrial septal aneurysm (ASA), or PFO. There are three types of ASD—ostium secundum, ostium primum, and sinoseptal defects. Ostium secundum ASDs are a result of abnormal development of the septum primum with failure to cover the fossa ovalis. This is the most common type of ASD, representing approximately 75% of all ASDs. Inadequate development of the endocardial cushion with failure to close the ostium primum results in an ostium primum ASD. Because the anterior leaflet of the mitral valve also develops from the endocardial cushion, ostium primum defects are almost always associated with a cleft anterior mitral leaflet. Such defects are most commonly seen in Down syndrome. Ostium primum defects constitute approximately 15% of ASDs. Sinoseptal defects are the least common, representing only 10% or less of all ASDs. Sinoseptal defects result from abnormal embryologic evolution of the sinus venosus and sinus valves. The most common is the sinus venosus ASD, which is located near the inflow of the superior vena cava and is usually associated with anomalous pulmonary venous return from part or all of the right lung, either directly into the right atrium, or into to the superior vena cava.

Under normal circumstances, ASDs allow flow from the left to right atrium with resultant right-sided volume overload and enlargement of the right atrium and ventricle. The hemodynamic consequences depend on the size of the ASD. With transient reversals of interatrial pressure as may occur with straining, coughing, Valsalva, anti-G straining maneuvers, or positive pressure breathing, flow may be reversed and ASDs could hypothetically serve as a conduit for embolic material, whether clot or venous gas bubbles.

The development of symptoms or complications from ASDs depends on the magnitude of the shunt. ASDs with shunts greater than a 1.5 pulmonary-to-systemic flow ratio generally produce significant right ventricular volume overload with resultant symptoms, including easy fatigue, dyspnea, especially on exertion, and arrhythmias, especially atrial fibrillation. Undetected, ASDs may go on to cause pulmonary hypertension with reversal of the shunt (Eisenmenger syndrome). In aircrew, who by nature of their job undergo frequent periodic medical screening, ASDs are most likely to be detected while still asymptomatic, during clinical examination, ECG or chest x-ray, or on an echocardiogram. Even after closure of an ASD, patients are at increased risk for atrial arrhythmias, especially atrial fibrillation, particularly if pulmonary artery pressures have been elevated.

ASDs typically have a fixed split second heart sound which lacks variability with respiration, and a right ventricular systolic outflow murmur (a midsystolic murmur heard best along the upper left sternal border). Careful auscultation may reveal an early diastolic rumble reflecting the volume overload flow across the tricuspid valve, heard best just to the right of the lower sternum. The ECG may show a mild right ventricular conduction delay (RSR′ in V1/V2), and a frontal axis greater than 90 degrees. The chest x-ray may show prominent main and branch pulmonary arteries, and right ventricular enlargement.

TTE is usually the procedure of choice for demonstrating and assessing an ASD. Flow across the septum can be demonstrated with color Doppler, and right atrial and ventricular chamber sizes can be determined. Pulmonary to systemic blood flow ratio can be quantified using Doppler techniques.

Closure of ASDs may be performed by direct surgical repair, or more recently by transcatheter devices. These involve the deployment of an occlusion device from a femoral venous approach. The devices work best in patients with centrally located secundum defects. Closure is indicated clinically for ASDs with pulmonic-to-systemic flow ratios greater than 1.5 and right ventricular enlargement, and for improvement of symptoms.

Aeromedical disposition of ASDs depends on the type of ASD and the magnitude of any associated shunt. The aeromedical concerns would be the potential for right-to-left shunting of blood clots or venous gas emboli. Hemodynamically insignificant ASDs are of no aeromedical consequence and may be considered for entry into flying training or for continued unrestricted flying. Prognosis after successful and uncomplicated closure of significant secundum ASD is normal if repair is performed for candidates younger than 25 years. Prognosis is significantly reduced for repairs performed after age 25, due to late occurrence of atrial fibrillation, stroke, and right heart failure. Successful ASD repairs performed earlier than age 25 are candidates for flying training and unrestricted flying if there is no residual shunt and cardiac structures and functions are normal. Repairs performed after age 25 should be considered on a case-by-case basis and followed more carefully. Prognosis for repaired sinus venosus ASD is similar to that of secundum ASD and may be treated similarly (1). Prognosis after repair of other ASDs is often not as favorable as for secundum ASD. These should be considered on a case-by-case basis. Again, repair at an early age offers the best outcomes. Specifically, repaired ostium primum ASD may experience concerning late events, such as significant mitral or tricuspid regurgitation, atrial fibrillation, and conduction defects (1).

Patent Foramen Ovale

Persistent patency of the foramen ovale into adult life is relatively common, and is normally of no hemodynamic consequence. The incidence of PFOs in autopsy series is approximately 25%, decreasing with age from 34% in the first three decades to 25% in the fourth to eighth decades. The average foramen size increases with age, with an overall average of 4.9 mm (44).

Clinical examination cannot detect PFOs. TEE with color flow or contrast injection is considered the "gold standard" for PFO detection, with close to 100% sensitivity for detection of PFOs compared to autopsy. Howver, TEE is an invasive and unpleasant procedure not without risk. TTE shows good specificity when compared to TEE, but suffers from lack of sensitivity, which is reported as less than 50%. This may be improved by the use of contrast agents, such as saline bubble infusion, together with a concurrent provocative maneuver such as a Valsalva strain, but TTE is still less than satisfactory as a stand-alone screening tool. ASAs and Chiari networks are associated with an increased prevalence of PFOs, and the presence of either on a TTE should intensify the search for a PFO.

The pressure difference between left and right atrium is usually small, approximately 5 mm Hg, and provocative maneuvers such as a Valsalva or anti-G strain may transiently reverse the pressure after release of the strain. Contrast imaging, for example, with a saline bubble infusion agitated in a double syringe system and injected to reach the right atrium just as the strain is released, increases the sensitivity for detection of a right to left shunt. Using contrast injection increases the sensitivity of TTE or TEE for detecting a PFO. Inferior vena caval flow, which courses along the atrial septum, may divert superior vena caval flow away from the septum, resulting in false-negative contrast infusions injected from the arm.

Because of the frequent occurrence of PFO and the low risk of events, most licensing agencies would consider asymptomatic, incidentally discovered PFOs to be acceptable for selection into flying training and for unrestricted flying duties. The aeromedical concerns relate to the hypothetical potential for PFOs as right-to-left conduits for blood clots, causing stroke, or for venous gas emboli resulting from altitude decompression, with resulting central nervous system DCS.

Cerebrovascular accidents (CVAs) (stroke or transient ischemic event) are uncommon in the aviator population but in this generally younger population, a PFO might serve as a substrate for embolic CVA. The incidence of PFO is particularly high (>50%) in cases of cryptogenic stroke where no other cause is identifiable. Careful screening for a right to left shunt including a PFO should be included in the evaluation of any aviator suffering an unexplained cerebrovascular event. Detection of a PFO as a substrate for such an event may allow consideration for a return to flying duties if there are no neurologic sequelae of aeromedical significance, and with successful closure of the PFO.

Most information regarding the increased risk for type II DCS with PFO is derived from diving studies. Although similar, in that decompression is involved in both, altitude and diving exposures are physiologically not equivalent and data from diving is neither directly applicable nor directly transferable to altitude DCS scenarios.

Retrospective analysis of diving data has demonstrated an increased relative (2–3 times) risk for type II DCS, particularly with early involvement of the brain, in divers with PFO, although the absolute risk remains low. MRI studies of sports divers have demonstrated significantly more ischemic brain lesions [(the white matter lesions that have been described in this context are unfortunately not very specific and are often the equivalent of "leucoaraiosis" = "white matter lesion" that are seen in many of our general patients) and association is not equal to causation] in divers with and without PFO compared to control subjects, but the divers with PFOs had a 4.5 fold increase in DCS events, and twice as many ischemic brain lesions than divers without PFO (45). On the basis of such information, it would seem prudent to screen aircrew who develop type II DCS during or following altitude decompression for any right to left shunt including a PFO.

Treatment of individuals with a PFO and CVA or DCS event remains controversial. While transvenous placement of PFO closure devices is an increasingly mature technique with excellent results, closure of a PFO in individuals who have suffered a CVA or DCS event necessarily implies that the PFO is believed to have been causal. However, the assumption of causality in individuals with a PFO and CVA or DCS is highly uncertain. The clinical literature is heterogeneous with respect to investigations addressing causality of PFOs in CVA and DCS. Previous prospective and retrospective studies of high quality have often reached incongruent conclusions regarding causality of PFO in cryptogenic stroke and DCS; therefore, the clinical and aeromedical disposition of individuals who have suffered from these events must by nature be highly individualized. The finding of a PFO in any given individual alone is insufficient to imply causality given the high incidence of PFOs in the overall population. Therefore, decisions regarding PFO closure and/or resumption of aeromedical duties are best made on case-by-case basis. Until a clearer picture of the causal relationship emerges, a “one-size fits all” aeromedical policy could result in unnecessary treatment procedures or suboptimal aeromedical disposition.

Atrial Septal Aneurysms

ASAs are not detectable on clinical examination and are usually discovered incidentally on echocardiography carried out for aeromedical screening purposes, or as part of a cardiac investigation. An ASA is defined on echocardiography by protrusion of the atrial septum greater than or equal to 15 mm beyond the plane of the interatrial septum or phasic excursion of the septum greater than or equal to 15 mm total amplitude during the cardiorespiratory cycle, with the diameter of the base of the aneurysmal portion measuring greater than or equal to 15 mm. The prevalence of ASAs in the general population is approximately 2%. They are frequently associated with a PFO, and both may act as a substrate for thromboembolic stroke (46).

From an aeromedical standpoint, while both PFO and ASA carry an increased relative risk for thromboembolic stroke, the absolute risk remains low. Because of the low absolute associated risk, ASAs should not be a disqualification for unrestricted licensing. With respect to medical selection for flying training, the issue is similar to BAV and involves a policy decision with respect to the risk assessment of investment of training dollars.

For aviators who do have a thromboembolic event and are found to have an ASA or PFO, and provided there is complete neurologic recovery, repair of the aneurysm or closure of the PFO surgically or with a transcatheter device may eliminate or minimize the risk for a recurrent event and allow a return to flying.

Ventricular Septal Defect

Because of the prominent auscultatory finding of a harsh pansystolic murmur along the left sternal border, previously undiagnosed ventricular septal defects (VSDs) are unlikely to present in trained aircrew. Small, hemodynamically insignificant VSDs present no increased risk from an aeromedical standpoint, and such individuals are medically fit for military pilot training and civilian licensing. Large hemodynamically significant VSDs create a significant left-to-right shunt with the development of pulmonary hypertension and pulmonary occlusive vascular disease. Such defects are generally surgically closed in early childhood, but later prognosis depends on the age at which repair occurred as well as pulmonary vascular complications. Repair before age 2 results in a good long-term prognosis, and such individuals are generally acceptable for military pilot selection and civilian licensing. Candidates for aircrew selection or licensing with VSDs repaired after age 2 require case-by-case assessment for pulmonary vascular resistance and pressures, and assessment for arrhythmias and conduction disturbances.

Patent Ductus Arteriosus

Likewise, a patent ductus arteriosus (PDA) is an unlikely finding in candidates for aircrew training or licensing because of the prominent continuous murmur heard best in the second left intercostal space, reflecting the continuous flow across the left-to-right shunt. Significant PDAs are almost always closed in childhood with surgical ligation through thoracotomy. Individuals with successfully repaired PDAs are acceptable for military aircrew training and civilian licensing. Evaluation should include assessment for any residual shunt, normal right ventricular function, and normal pulmonary vascular resistance and pressures.

Coarctation of the Aorta

Coarctation of the aorta is usually diagnosed in childhood, but may not be discovered until adulthood. The localized narrowing in the aortic arch usually occurs just distal to the left subclavian artery, resulting in a pressure differential between upper and lower extremities. Associated disorders include BAV, aneurysm of the aorta proximal or just distal to the coarctation, and cerebrovascular aneurysms. The diagnosis should be suspected with the finding of elevated blood pressures in the arms, and diminished pulses and blood pressures in the legs. Coarctations are generally discovered and repaired in childhood, but even after repair the aorta remains abnormal with risk of aneurysm, dissection, and rupture. Long-term prognosis is related to age of repair, with the best outcome for correction under age 9 (1). Because of the continuing risk even after surgery, individuals with repaired coarctations are considered unfit for military pilot training. Medical certification for licensing is predicated on the age of correction and outcome. Evaluation should include assessment for hypertension at rest and with exercise, and evaluation of left ventricular structure and function with echocardiography or nuclear imaging. The prognosis of insignificant coarctations with gradients less than 20 mm Hg is not well defined, and such individuals are likely acceptable for medical certification.

Hypertrophic Cardiomyopathy

Estimated prevalence of HCM is 0.02% to 0.2%. Screening echocardiograms performed in more than 20,000 USAF pilot candidates have revealed no cases of HCM. Spontaneous cases are common but approximately 50% are inherited in an autosomal dominant pattern with variable penetrance and clinical expression. HCM may be classified as obstructive or nonobstructive; only approximately 25% have a dynamic obstruction across the left ventricular outflow tract. The presence and severity of left ventricular outflow tract obstruction are not related to sudden death or to symptoms. Most patients are asymptomatic or mildly symptomatic, but symptoms can be severe and are often exertion related. Although most sudden deaths occur at rest or with mild exertion, approximately one third occur during or just after vigorous activity.

Annual mortality rates of 1% per year or less are reported in various community populations and asymptomatic subjects. Sudden death is most common in younger subjects but may occur in middle age, even without prior symptoms. Markers for sudden death include young age at diagnosis, syncope, family member with HCM and sudden death, some genetic markers, severe hypertrophy, and nonsustained VT. Progression to dilated cardiomyopathy occurs in 10% to 15% and atrial fibrillation in another 10%.

Nonsustained VT on ambulatory monitoring, hypotension during graded exercise test, and a history of syncope may predict mortality greater than 1% per year. Absence of these factors predicts a mortality risk less than 1% per year. Nonfatal events such as presyncope, lightheadedness, chest pain, and dyspnea increase the aeromedically pertinent event rate to greater than 1% per year, on the order of 5% per year.

Military, commercial, and aerobatic flying are not recommended. Generally, private aviation might be considered for asymptomatic low-risk subjects. Annual 24- to 48-hour ambulatory monitoring, graded exercise testing, and echocardiography are recommended. Published guidelines for competitive athletes similarly recommend against participation except for select low-intensity sports, regardless of age, gender, symptom status, presence/absence of outflow obstruction, or treatment.

TACHYARRHYTHMIAS AND RADIOFREQUENCY ABLATION

Tachyarrhythmias are a significant aeromedical concern because of their sudden, often unpredictable onset and possible hemodynamic symptoms that might impair flying performance. Medications to suppress tachyarrhythmias were previously the primary therapeutic option and such therapy has its own clinical and aeromedical concerns. Perfect control is often unattainable and should not be assumed—the possibility of the tachyarrhythmia "breaking through" the medication must always be considered. And medications may have concerning side effects, especially the proarrhythmic effect of many antiarrhythmic medications. Radiofrequency ablation offers a curative approach for many tachyarrhythmias with return to restricted or even unrestricted flying duties for aviators who previously may have been permanently disqualified.

For purpose of this discussion, tachyarrhythmias will be defined as three or more consecutive ectopic supraventricular or ventricular beats at a rate of 100 beats/minute or faster.

Supraventricular Tachyarrhythmias

Atrioventricular Node Reentrant Tachycardia

This is the most common type of SVT, comprising approximately 60% of all instances of SVT. Dual or multiple pathways within the AV node create a micro reentrant circuit within the AV node. Most electrophysiologists consider that once an initial episode has occurred, atrioventricular node reentrant tachcardia (AVNRT) will recur throughout a patient's lifetime. Electrophysiology literature reports recurrence rates as high as 70% within a few months. However, such data are from tertiary center experience and likely suffer from referral bias. Recent experience regarding all SVT mechanisms from community-based studies and a military aviator population suggest recurrence rates of 10% per year or less after an initial episode of sustained SVT (1).

Atrioventricular Reentrant Tachycardia

This second most common type of SVT comprises approximately 30% of cases. Atrioventricular reentrant tachycardia (AVRT) involves a macro reentrant circuit involving an accessory pathway or bypass tract. WPW is the most common such condition. Usually, the direction of propagation of SVT is antegrade down the AV node pathway and retrograde up the accessory pathway, yielding a narrow QRS complex SVT. In occasional patients, the direction of SVT propagation is reversed, antegrade down the accessory pathway and retrograde up the AV node pathway, yielding a wide QRS complex SVT that may easily be mistaken for VT.

Other Supraventricular Tachycardias

Uncommon mechanisms comprise the remaining 10% of SVT cases, including automatic atrial tachycardia, intra-atrial reentrant tachycardia, and sinus node reentrant tachycardia.

Aeromedical Disposition of Supraventricular Tachycardia

The aeromedical concern is the risk of recurrent sustained episodes of SVT and possible symptoms that may incapacitate the aviator or otherwise adversely affect flying performance. SVT with associated hemodynamic symptoms (e.g., syncope, presyncope, lightheadedness) should be disqualifying for flying duties. Multiple episodes of sustained SVT, even without hemodynamic symptoms, should also probably be disqualifying because of the likelihood of future episodes and unreliability of medical control. If waiver is considered for medically controlled SVT, the most likely candidates for such clearance are digitalis preparations, β-blockers, and calcium channel antagonists. Cure of the SVT by radiofrequency ablation (discussed in the subsequent text) may also be eligible for waiver.

The aeromedical disposition of a single sustained episode of SVT without hemodynamic or other significant symptoms is more flexible. With possible recurrence rates of 10% or less per year, return to some categories of flying duties may be feasible, even in the absence of medical therapy. The USAF has returned such aviators to unrestricted flying duties for many years without incident (1).

Aeromedical Disposition of Atrial Flutter and Atrial Fibrillation

Atrial flutter is often associated with atrial fibrillation but may occur as an isolated rhythm disturbance. It presents unique considerations. In an otherwise healthy and unmedicated individual, the atrial rate is approximately 300 beats/minute and AV conduction is often 2:1, yielding a ventricular rate of 150 beats/minute. And 1:1 conduction, with a ventricular rate of 300 beats/minute, is quite possible, especially in young subjects. Although this may be tolerated well, such rates are certainly concerning. Medical therapy is required to increase the AV block ratio and thereby control ventricular rate. Because of the possibility of rapid ventricular rates, licensing authorities may consider atrial flutter disqualifying for flying duties. However, select cases that are well controlled by medication may be considered acceptable for private aviation.

Atrial fibrillation may occur as a consequence of underlying cardiac pathology, especially valvular disease. In such cases, aeromedical disposition should be determined by the underlying process, as discussed elsewhere in this chapter. Lone atrial fibrillation is considered here—atrial fibrillation in the absence of demonstrable underlying cardiac disease. Within the definition of lone atrial fibrillation, most authors also exclude hypertension and age older than 60 years. Lone atrial fibrillation may present as one of three distinct entities: a single, isolated episode of atrial fibrillation; recurrent paroxysms of atrial fibrillation; or persistent, chronic atrial fibrillation.

Single episodes often have an identifiable precipitating cause, such as acute abuse of alcohol and/or other stimulants (holiday heart syndrome). Single episodes are also frequently self-limited and convert spontaneously to normal sinus rhythm. Paroxysmal and chronic lone atrial fibrillation are often asymptomatic in otherwise healthy subjects, although inadequate cardiac output response to stress and reduced exercise tolerance may be present. Risk of stroke in lone atrial fibrillation is typically less than 1% per year, negating the need for warfarin anticoagulation. As with atrial flutter, medication is often indicated for ventricular rate control for paroxysmal or chronic atrial fibrillation. Even if the ventricular rate is not accelerated under resting conditions, it typically accelerates quickly and excessively with exertion or stress. Again, digitalis preparations, β- blockers and calcium channel antagonists are aeromedically most acceptable. Other medications have unacceptable side effects, including proarrhythmia.

A single episode of atrial fibrillation without associated hemodynamic symptoms may be acceptable for return to flying duties, including unrestricted military flying, after an observation period of a few months and exclusion of underlying cardiac disease. Paroxysmal or chronic lone atrial fibrillation may be acceptable for military and civilian flying duties if asymptomatic with good exercise tolerance and good control of ventricular rate, including graded exercise testing. Restriction to low-performance aircraft is recommended; both atrial fibrillation itself and rate controlling medications may reduce $+G_z$ tolerance. Ablation of atrial fibrillation, discussed later, offers possible return to high-performance flying. Reassessment at 1- to 3-year intervals is appropriate.

Ventricular Tachycardia

Mention of VT usually elicits a strong visceral response in clinical and aeromedical practitioners. Most clinical and literature experience deals with sustained or hemodynamically symptomatic VT. Here, the aeromedical disposition seems obvious—removal from all categories of flying. More often, the aeromedical dilemma will involve the disposition of nonsustained runs of VT without hemodynamic symptoms.

When associated with some cardiac diseases, such as CAD or cardiomyopathy, the presence of nonsustained VT carries additive risk for adverse cardiac events. In the presence of other, "unrelated" cardiac disorders, there appears to be no increased risk from nonsustained VT. These entities should be treated aeromedically like idiopathic nonsustained VT. When there is no underlying cardiac disease, the arrhythmia is termed *idiopathic VT*. Cardiac literature suggests, and most cardiologists would advise, that idiopathic nonsustained VT is benign. However, most literature on idiopathic nonsustained VT considers sudden cardiac death as the only primary endpoint. Many articles do not address the issue of syncope and even fewer address the occurrence of presyncope, lightheadedness, dyspnea, and other hemodynamic symptoms. These consequences are certainly of aeromedical concern.

Another consideration is the frequency and duration of nonsustained VT episodes. Cardiac literature does support a benign prognosis for infrequent episodes of short-duration VT (a few beats to several beats duration). Prognosis is not well-defined for frequent episodes or episodes longer than four to ten beats' duration. Recent USAF experience reflects these data (1,3). In 103 military aviators with asymptomatic idiopathic nonsustained VT, the annual event rate for sudden cardiac death, syncope, presyncope, or sustained VT was less than 0.5% per year during a mean follow-up of approximately 10 years. However, the majority had VT runs of only three beats' duration and only one VT episode per 24-hour ambulatory ECG recording. Only 10% had more than four episodes of nonsustained VT per 24-hour ambulatory recording and only 3% had VT episodes longer than ten beats duration. On the basis of this data, USAF guidelines recommend no more than four episodes per 24-hour ambulatory ECG recording and duration of 11 beats or less for return to unrestricted flying.

Aeromedical Disposition of Ventricular Tachycardia

Noninvasive evaluation is required to exclude underlying cardiac pathology, especially CAD and cardiomyopathy. A minimum of graded exercise testing, echocardiography, 24-hour ambulatory ECG recording, and examination for coronary artery calcification are recommended. Exercise radionuclide imaging or stress echocardiography are a consideration, especially in older male aviators, postmenopausal female aviators, or other higher-risk situations. Consideration of coronary angiography should be guided by noninvasive test results.

Disqualification from all categories of flying is recommended for sustained VT and any duration VT with associated hemodynamic symptoms. If nonsustained VT is asymptomatic but associated with an underlying disease that increases risk, such as cardiomyopathy or CAD, disqualification may be appropriate, particularly for military aviation and commercial flying.

The risk of frequent or long-duration runs of nonsustained idiopathic VT is not clear. A prudent policy for nonsustained idiopathic VT should limit the number and duration of episodes. Published recommendations for competitive athletics recommend return to full athletic competition for episodes with duration of approximately 10 beats or less. Recommendations regarding acceptable frequency of episodes are usually lacking. Current USAF guidelines recommend no more than four episodes per 24-hour ambulatory ECG recording and duration of 11 beats or less for return to unrestricted flying.

Radiofrequency Ablation of Tachyarrhythmias

Atrioventricular Node Reentrant Tachycardia and Atrioventricular Reentrant Tachycardia

Ablation success rates for these two SVT mechanisms are similar and well reported. In experienced laboratories, the immediate success rate is 95% or greater; repeat ablation for initial failures is also 95% or more successful. Cure is therefore possible for nearly all cases. Recurrence of a functional reentrant circuit after apparent immediate success is 5% or less. Most clinical recurrences appear within 2 to 4 months of ablation and late recurrences are reportedly unusual. Clinically, recurrence is typically defined as recurrence of SVT or return of the WPW ECG pattern (for that disorder). The complication rate is low, but includes the possibility of complete heart block and subsequent requirement for permanent cardiac pacing. This risk is inherent to ablation performed on or near the anterior surface of the AV node. Regarding AVRT, approximately 5% to 10% of accessory pathways are located in this dangerous area; risk of complete heart block for such cases is 5% to 10%. Ablation of AVNRT is typically performed on the posterior surface of the AV node; risk of complete heart block at this location is approximately1%.

Return to unrestricted flying duties is considered for successful, uncomplicated ablation. A nonflying observation period of 3 to 4 months is appropriate to get beyond the window of most clinical recurrences. The appropriate documentation of successful ablation is an important aeromedical decision. Initial USAF policy required follow-up electrophysiologic testing no sooner than 3 months after ablation. Results were consistently negative, so this requirement was eliminated. Current USAF policy requires only a nonflying observation period of 4 months with no arrhythmia symptoms, no SVT, and normal ECG. Ambulatory ECG recording and graded exercise testing may be performed; in the USAF experience they were also nonproductive. Follow-up electrophysiologic testing should be considered for SVT with associated significant hemodynamic symptoms.

Other Supraventricular Tachycardias

As stated previously, these are unusual tachyarrhythmias that are primarily automatic atrial tachycardias. There is less-reported literature experience for ablation of these compared to AVNRT and AVRT, especially with long-term follow-up. However, reported outcomes for ablation of these rhythm disturbances are similar to those for AVNRT and AVRT. Aeromedical disposition should probably be patterned from policies for ablation of AVNRT and AVRT and considered on a case-by-case basis.

Atrial Flutter

Atrial flutter is a reentrant tachyarrhythmia with the reentry circuit located near the tricuspid valve. As such, it is quite amenable to ablation. Success rates are 95% or better with no significant complications. Aeromedical considerations are similar to those of AVNRT and AVRT given in the preceding text, plus post–ablation atrial fibrillation, reported in 20% to 30%. A patient may therefore have successful ablation for atrial flutter only to experience paroxysmal or chronic atrial fibrillation. This is more likely if atrial fibrillation was present before flutter ablation. Aeromedical disposition must then consider this additional complicating feature. Return to unrestricted flying duties is a consideration, after an observation period of approximately 6 months.

Atrial Fibrillation

Specific procedures for atrial fibrillation ablation are continuously under development and refinement. Success rates are procedure dependent and range 60% to 90% off all antiarrhythmic medications. Recurrence rates as high as 25% are reported, again mostly within 3 to 6 months (1). Late recurrence is more likely than for ablation of SVT mechanisms. An observation period of 4 to 6 months is recommended, with return to unrestricted flying if noninvasive testing is unremarkable. Graded exercise testing, 24-hour ambulatory monitoring, and echocardiography are recommended. In recent years, the USAF has returned several aviators to unrestricted flying after ablation of paroxysmal or chronic atrial fibrillation, with no reported problems or incidents to date.

Ventricular Tachycardia

A discussion of the disposition of radiofrequency ablation of VT is more difficult than for ablation of the various types of SVT. On the one hand, one might consider aeromedical disposition to be easy and simple, a disqualification for all flying duties. On the other hand, cardiologists who perform ablation may advise that the procedure is curative for idiopathic VT and therefore no risk for aviation. VT that has required ablation and is associated with underlying cardiac substrate, such as CAD or cardiomyopathy, should be disqualified for all classes of flying. The underlying disease substrate frequently gives rise to multiple foci of VT; in such cases ablation may only be palliative or an adjunct to other therapy, such as antiarrhythmic medications and implantable defibrillators. And the underlying disease itself may well be disqualifying.

Consideration of return to any flying duties should be limited to ablation of idiopathic VT. And here exists a paradox. VT ablation is likely to be clinically recommended for sustained or nonsustained VT, especially if frequent, symptomatic, or resistant to medical therapy. Although stating that ablation may be curative for idiopathic VT, some published guidelines recommend that ablation is contraindicated for asymptomatic, nonsustained idiopathic VT. In other words, the more serious and symptomatic cases present for consideration of return to flying duties after ablation.

The scenario is more complicated than for SVT ablations, with less reported experience and long-term follow-up. Also, electrophysiologic testing is less reliable to document a cure than for SVT ablations. And in the literature, "cure" of VT by ablation may mean only no recurrence of spontaneous or ECG-documented sustained VT and absence of hemodynamic symptoms. Episodes of nonsustained VT may persist and "cure" may mean that the rhythm is now controlled on antiarrhythmic medications. In other words, "cure" may not mean complete eradication of the VT and absence of any medications.

There are several mechanisms for VT. The most common mechanism and location for idiopathic VT may also be the most benign and most amenable to ablative "cure"—right ventricular outflow tract (RVOT) VT. This procedure holds promise for future aeromedical disposition, pending further information regarding long-term success and outcomes. In the interim, waiver for restricted flying may be considered on a case-by-case basis. If so, a longer observation period of 6 to 12 months is recommended, with thorough noninvasive evaluation and annual reassessment.

PERICARDITIS AND MYOCARDITIS

Pericarditis

In the aviator population, pericarditis will usually be viral or idiopathic, presumed viral. The aeromedical disposition of other etiologies (e.g., bacteria, tuberculosis, cancer, autoimmune disorders) should be on the basis of prognosis of the underlying disease and is not further considered. The acute phase of viral/idiopathic pericarditis usually follows a viral illness within a few weeks, and is characterized by fever, other constitutional symptoms, chest discomfort, pericardial friction rub, and serial ST-T wave ECG changes. This typically lasts 2 to 6 weeks, after which the course is typically benign. An aviator should be relieved of flight duties during the acute phase.

After the acute phase has resolved, the primary aeromedical concerns are recurrent pericardial pain and supraventricular arrhythmias. Late pericardial effusion, with or without tamponade, and development of chronic constrictive pericarditis are unusual. Approximately one fourth of patients reportedly develop recurrent chest pain within a few months of or even up to a year following the acute illness. Recurrent symptoms usually respond to nonsteroidal anti-inflammatory agents or colchicine; rarely steroids may be required. There is no helpful data regarding the likelihood of supraventricular arrhythmias, although they are known to occur.

To avoid complications, such as recurrent chest pain, recurrent pericardial effusion, and arrhythmias, a prudent aeromedical policy would include a time of nonflying observation after the acute phase, including a period of time after discontinuation of medications. Observation for 2 to 3 months after resolution of symptoms and at least 1month after discontinuation of anti-inflammatory medication should be sufficient for most cases. At that time, evaluation with echocardiography and ambulatory monitoring is recommended.

Graded exercise testing might be considered to exclude exertion-induced arrhythmias or to document normal exercise tolerance, but is not routinely recommended. It is unlikely to be helpful if there have been no arrhythmias by clinical presentation or ambulatory monitoring and no evidence of associated myocarditis. Additionally, the ST-T wave changes of pericarditis may require weeks to months to resolve and may cause secondary ST depression during graded exercise testing, adding unnecessary confusion to the case.

Late complications are unusual and unlikely in the absence of symptoms or signs; routine reassessment is therefore not required for uncomplicated viral/idiopathic cases. After clinical resolution, the specified observation period and acceptable findings on follow-up examination, return to unrestricted flying duties can be recommended.

Myocarditis

In the aviator population, myocarditis is also most often caused by a viral infection, but the possible consequences may be much more significant. The spectrum of presentation ranges from undetected, subclinical infection to rapidly progressive and fatal congestive heart failure. Myocarditis and pericarditis share common viral etiologies and myocarditis may often accompany or complicate pericarditis. Viral myocarditis is probably more common than clinically diagnosed; many cases of idiopathic-dilated cardiomyopathy are very likely the end result of undiagnosed viral myocarditis.

Viral myocarditis may cause dilation of cardiac chambers, ventricular systolic dysfunction, heart failure, arrhythmias, and conduction disturbances. Although recovery is typically complete, dilated cardiomyopathy may be the end result, appearing either during the acute phase or as a delayed effect after a latent, asymptomatic period.

Aeromedical disposition should require resolution of symptoms and recovery of cardiac chamber sizes and function to normal or near normal. A nonflying period of observation is recommended; most sources would probably suggest 6 months. Subsequent aeromedical assessment should test for cardiac recovery, functional capacity, and arrhythmias. This would include echocardiography, 24-hour ambulatory ECG monitoring, and graded exercise testing with either stress echocardiography to assess ventricular function at peak stress. Return to unrestricted flying duties may be recommended if recovery is documented—good functional capacity, normal or near normal cardiac chamber sizes and function, and no significant arrhythmias. Because dilated cardiomyopathy may appear late, periodic reassessment is also recommended.

SUMMARY

Within the aerospace medicine community, we aeromedical practitioners often express our mission as "to keep them flying—safely." Our necessarily conservative approach often gains us a much different reputation in the view of the aviator and our clinical colleagues. Ours is a unique medical practice with less of the intrinsic reward inherent to clinical medicine. Requiring solid safety and outcomes data, we are generally limited to well-validated, established resources rather than the most recent medication, the latest test, or the hottest new procedure. However, it is a unique medical environment and aerospace cardiology is only one of its many fascinating aspects.

In this chapter, we have been able to only briefly discuss some of the more important issues regarding cardiac disorders and aeromedical decision making. It would have been very difficult, even impossible, to give the reader irrefutable data supporting ironclad aeromedical dispositions for all cardiac diagnoses. With such a broad spectrum of civilian and military aviation categories, different opinions and philosophies, and so on, aerospace medicine truly demonstrates that medical practice is as much an art as it is a science. Rather we sought to illustrate an aeromedical decision-making process that can be applied to most, if not all, diagnoses, ranging from common cardiac disorders to one-of-a-kind cases. Select an event rate threshold, define appropriate aeromedical events, determine annual event rates, consider special situations (e.g., high $+G_z$), formulate a recertification policy, consider the impact of other endpoints and therapy and . . . KEEP′ EM FLYING—SAFELY.

REFERENCES

1. Kruyer WB. Cardiology. In: Rayman RB, ed. *Clinical aviation medicine*, 4th ed. New York: Professional Publishing Group, Ltd, 2006:147–276.
2. Hiss RG, Lamb LE. Electrocardiographic findings in 122,043 individuals. *Circulation* 1962;25(6):947–961.
3. Gardner RA, Kruyer WB, Pickard JS, et al. Nonsustained ventricular tachycardia in 193 U.S. military aviators: long-term follow-up. *Aviat Space Environ Med* 2000;71(8):783–790.
4. American Heart Association. *2001 Heart and stroke statistical update*. Dallas: American Heart Association, 2000.
5. Marso SP, Griffin BP, Topol EJ. *Manual of cardiovascular medicine*. Philadelphia: Lippincott Williams & Wilkins, 2000.
6. Nissen S. Coronary angiography and intravascular ultrasound. *Am J Cardiol* 2001;87(Suppl):15A–20A.
7. Pathobiological Determinants of Atherosclerosis in Youth (PDAY) Research Group. Natural history of aortic and coronary atherosclerotic lesion in youth. Findings from the PDAY Study. *Arterioscler Thromb* 1993;13(9):1291–1298.
8. Yusuf S, Hawken S, Ounpuu S, et al. Effect of potentially modifiable risk factors associated with myocardial infarction in 52 countries (the INTERHEART study): case control study. *Lancet* 2004;364(9438):937–952.
9. Danesh J, Collins R, Petro R. Lipoprotein (a) and coronary heart disease. Meta-analysis of prospective studies. *Circulation* 2000;102:1082–1085.
10. Gami AS, Witt BJ, Howard DE, et al. Metabolic syndrome and risk of incident cardiovascular events and death. *J Am Coll Cardiol* 2007;49(4):403–414.
11. Leander K, Hallqvist J, Reuterwall C, et al. Family history of coronary heart disease, a strong risk factor for myocardial infarction interacting with other risk factors: results of the Stockholm Heart Epidemiology Program (SHEEP). *Epidemiology* 2001;12: 215–221.
12. Lloyd-Jones DM, Ham BH, D'Agostino RB, et al. Parental cardiac disease as a risk factor for cardiovascular disease in middle aged adults: a prospective study of parents and offspring. *JAMA* 2004;291:2204–2211.
13. Pearson TA, Mensah GA, Alexander RW, et al. Markers of inflammation and cardiovascular disease. Application to clinical and public health practice. A statement for health care professionals from the AHA/CDC. *Circulation* 2003;107:499–511.
14. Ridker PM, Cook N. Clinical usefulness of very high and very low levels of C-reactive protein across the full range of Framingham risk scores. *Circulation* 2004;109:1955–1959.
15. National Cholesterol Education Program, National Heart, Lung and Blood Institute. *Detection, Evaluation and Treatment of High Blood Cholesterol in Adults (Adult Treatment Panel III)*. National Institutes of Health Publication No 01–3670, May 2001.
16. Grundy SM, Cleeman JI, Merz CNB, et al. Implications of recent trials for the National Cholesterol Education Treatment Program Adult Treatment Panel III guidelines. *Circulation* 2004;110:227–239.
17. McPherson R, Frohlich J, Fodor G, et al. Canadian Cardiovascular Society position statement–recommendations for the diagnosis and treatment of dyslipidemia and prevention of cardiovascular disease. *Can J Cardiol* 2006;22(11):913–927.
18. Metz LD, Beattie M, Hom R, et al. The prognostic value of normal exercise myocardial perfusion imaging and exercise echocardiography. A meta-analysis. *J Am Coll Cardiol* 2007:49(2): 227–237.
19. Gibbons RJ, Balady GJ, Bricker TJ, et al. ACC/AHA 2002 guideline update for exercise stress testing: summary article. *Circulation* 2002;106:1883–1892.
20. Gibbons LW, Mitchell TL, Wei M, et al. Maximal exercise test as a predictor of risk for mortality from coronary heart disease in asymptomatic men. *Am J Cardiol* 2000;86:53–58.
21. Fleishmann KE, Hunink MG, Kuntz KM, et al. Exercise echocardiography or SPECT imaging? A meta-analysis of diagnostic test performance. *JAMA* 1998;280:913–920.
22. Smalley BW, Loecker TH, Collins TR, et al. Positive predictive value of cardiac fluoroscopy in asymptomatic U.S. Army aviators. *Aviat Space Environ Med* 2000;71:1197–1201.
23. Loecker TH, Schwartz RS, Cotta CW, et al. Fluoroscopic coronary artery calcification and associated coronary disease in asymptomatic young men. *J Am Coll Cardiol* 1992;19:1167–1172.
24. Nasir K, Raggi P, Rumberger JA, et al. Coronary artery calcium volume scores on electron beam tomography in 12,936 asymptomatic adults. *Am J Cardiol* 2004;93:1146–1149.

25. Hamilton DR, Murray JD, Ball CG. Cardiac health for astronauts: coronary calcium scores and CRP criteria for selection and retention. *Aviat Space Environ Med* 2006;77:377–387.
26. Pilote L, Dasgupta K, Guru V, et al. A comprehensive review of sex-specific issues related to cardiovascular disease in women. *CMAJ* 2007;176(Suppl 6):S1–S44.
27. Osswald S, Miles R, Nixon W, et al. Review of cardiac events in USAF aviators. *Aviat Space Environ Med* 1996;67:1023–1027.
28. Edmond M, Mock MB, Davis KB, et al. Long-term survival of medically treated patients in the Coronary Artery Surgery Study (CASS) registry. *Circulation* 1994;990:2645–2657.
29. Hueb WA, Soares PR, Oliveira SA, et al. Five-year follow-up of the Medicine, Angioplasty, or Surgery Study (MASS). *Circulation* 1999;100(Suppl 19):II107–II113.
30. Gray GW. Cardiovascular and pulmonary disease in NATO aircrew—an overview. In: *Cardiopulmonary aspects of aerospace medicine, Advisory Group for Aerospace Research and Development (NATO) Lecture Series 189*. Loughton, Esse: Specialized Printing Services Limited, 1993:1–1–1–5.
31. Gray GW, Salisbury DA, Gulino AM. Echocardiographic and colour flow Doppler findings in military pilot applicants. *Aviat Space Environ Med* 1995;66:32–34.
32. Strader J, Adair A, Kruyer W. Efficacy of United States Air Force Pilot Applicant Screening Echocardiography [abstract]. *Aviat Space Environ Med* 2007;78(3):319. Aerospace Medical Association 78th Annual Scientific Meeting, May 2007.
33. AGARD Aerospace Medical Panel Working Group 18. Echocardiographic findings in NATO pilots: do acceleration (+Gz) stresses damage the heart? *Aviat Space Environ Med* 1997;68(7):596–600.
34. Barnett SL, Lopez FM, Strader JR Jr, et al. Echocardiographic follow-up of 52 military aircrew with bicuspid aortic valve [abstract]. *Aviat Space Environ Med* 2006;77(3):271. Aerospace Medical Association 77th Annual Scientific Meeting, May 2006.
35. Albery WB, Ten Eyck RP, Wolfe M. Female exposure to high G: echocardiographic evaluation for chronic changes in cardiac function. *Aviat Space Environ Med* 1998;69:857–861.
36. Albery WB. Echocardiographic evaluation of female centrifuge subjects for chronic changes in cardiac function. *Aviat Space Environ Med* 1999;70:561–564.
37. Lund O, Nielsen SL, Arildsen H, et al. Standard aortic St. Jude valve at 18 years: performance profile and determinants of outcome. *Ann Thorac Surg* 2000;69(5):1459–1465.
38. Jamieson WR, Burr LH, Munro AI, et al. Carpentier-Edwards standard porcine bioprosthesis: a 21 year experience. *Ann Thorac Surg* 1998;66(Suppl 6):S40–S43.
39. Ramirez A, Strader JR, Kruyer WB. A military pilot with aortic root and prosthetic aortic valve replacement for ascending aortic aneurysm [abstract]. *Aviat Space Environ Med* 2006;77(3):272. Aerospace Medical Association 77th Annual Scientific Meeting, May 2006.
40. Gleason T, David T, Coselli J. St. Jude medical toronto biologic aortic root prosthesis: early FDA phase II IDE study results. *Ann Thorac Surg* 2004;78:786–793.
41. Ward C. Clinical significance of the bicuspid aortic valve. *Heart* 2000;83:81–85.
42. Carter D, Pokroy R, Azaria B, et al. Effect of G-force on bicuspid aortic valve in aviators. *Cardiology* 2006;108(2):124–127.
43. Boudoulas H, Wooley CF. *Mitral valve: floppy mitral valve, mitral valve prolapse, mitral valvular regurgitation*, 2nd ed. Armonk: Futura Publishing, 2000.
44. Hagen P, Scholz D, Edwards W. Incidence and size of patent foramen ovale during the first 10 decades of life: an autopsy study of 965 normal hearts. *Mayo Clin Proc* 1984;59:17–20.
45. Schwerzmann M, Seller C, Lipp E, et al. Relation between directly detected patent foramen ovale and ischemic brain lesions in sport divers. *Ann Intern Med* 2001;134:21–24.
46. Overell JR, Bone I, Lees KR. Interatrial septal abnormalities and stroke: a meta-analysis of case-controlled studies. *Neurology* 2000;55(8):1172–1179.

RECOMMENDED READINGS

Bonow RO, chair. ACC/AHA 2006 guidelines for the management of patients with valvular heart disease. A report of the American College of Cardiology/American Heart Association task force on practice guidelines. *J Am Coll Cardiol*, 2006;48(3):e1–e148.

Braunwald E, Zipes DR, Libby P, Bonow RO, eds. *Braunwald's heart disease: a textbook of cardiovascular medicine*, 7th ed. Philadelphia: WB Saunders, 2004.

Joint National Committee on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure. The seventh report of the Joint National Committee (JNC-VII) on Prevention, Detection, Evaluation, and Treatment of High Blood Pressure. *JAMA*, 2003;289(19):2560–2572.

Joy M, ed. First European workshop in aviation cardiology. *Eur Heart J*, 1992;13(Suppl H):1–175.

Joy M, ed. Second European workshop in aviation cardiology. *Eur Heart J* 1999;1(Suppl D):D1–D131.

Joy M. Cardiovascular disease. In: Rainford DJ, Gradwell DP, eds. *Ernsting's aviation medicine*, 4th ed. London: Edward Arnold (Publishers) Ltd, 2006:567–604.

Kruyer WB, Gray GW, Leding CJ. Clinical aerospace cardiovascular medicine. In: DeHart RL, Davis JR, eds. *Fundamentals of aerospace medicine*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2002:333–361.

Maron BJ, Zipes DP, co-chairs. 36th Bethesda conference: eligibility recommendations for competitive athletes with cardiovascular abnormalities. *J Am Coll Cardiol* 2005;45(8):1313–1375.

CHAPTER 14

Ophthalmology in Aerospace Medicine

Thomas J. Tredici and Douglas J. Ivan

And God said, "Let there be light." Genesis 1:3

Vision has always held a dominant place in the attributes necessary for flying. This was recognized by early pioneers, such as Drs. William Wilmer and Conrad Berens, who established the first laboratory to study the visual problems of the flyer in 1918 at the Air Service Medical Research Laboratory at Mineola, Long Island, New York (1). This almost total dependence on vision is evident now, as astronauts have reported the necessity of vision for orientation in space. Vision occurs peripherally at the eye and centrally in the brain. In the eye, the retina receives electromagnetic energy (photons) and, through a photochemical reaction, converts it into electrical signals. The nervous impulses are relayed to the occipital area of the brain where the signals are processed and interpreted as vision.

APPLIED ANATOMY AND PHYSIOLOGY OF THE EYE

The human eyes are protected by bony orbits that are shaped like a quadrilateral pyramid, thereby allowing good exposure of the cornea anteriorly to facilitate vision. Posterior openings in the orbits allow cranial nerves and blood vessels from the brain to communicate with the eye. Six extraocular muscles rotate each eye in all directions of the visual field.

Globe

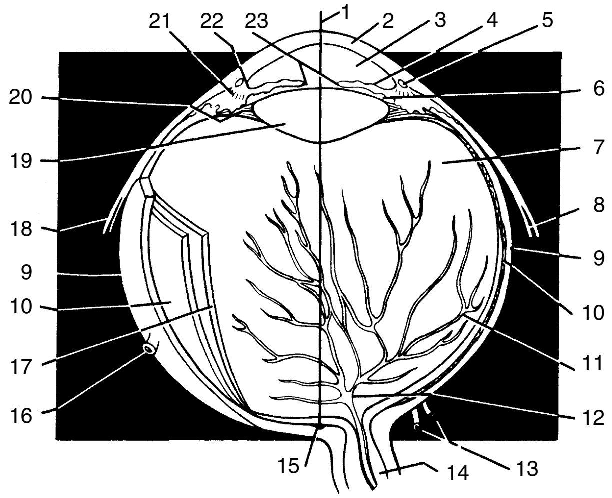
The globe measures approximately 25 mm in diameter and is composed of three coats. The two outer layers, the scleral and uveal coats, are involved with support, protection, and nutrition. The inner coat, the retina, contains the light sensitive elements. The clear cornea has a shorter radius (7.5 mm) than the sclera (12.0 mm) (Figure 14-1).

As shown in (Figure 14-2) the normal eye is a +60 D refractive system, +45 D supplied by the cornea and +15 D by the unaccommodated lens. Therefore, we see that small changes in the radius of curvature of the cornea can cause substantial changes in refraction. This can be accomplished by the use of contact lenses, (orthokeratology) or surgical procedures such as radial keratotomy (RK), photorefractive keratectomy (PRK), or laser *in situ* keratomileusis (LASIK), as well as other corneal refractive surgical (CRS) procedures.

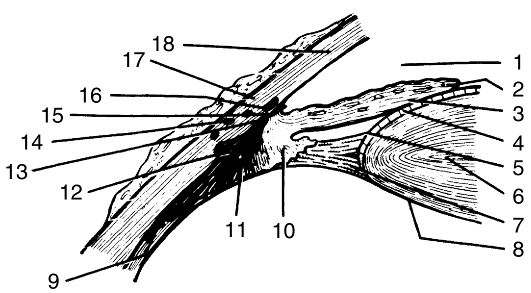
The uvea lies inside the scleral coat, it is the pigmented, vascular portion of the eye consisting of the choroid posteriorly, and the ciliary body and iris anteriorly. Aqueous humor is produced by diffusion and secretion in the epithelium of the ciliary processes. The ciliary muscle, innervated by the parasympathetic nervous system, supplies the contractile force necessary to change the shape of the lens during accommodation. The pupil is the opening in the iris. Its size is controlled by a delicate balance of the sympathetic and parasympathetic tone of the autonomic nervous system, principally in response to the level of illumination.

The intraocular lens lies just behind the iris, held in place by zonular fibers that are inserted into the lens capsule and the ciliary processes on the ciliary body (Figure 14-1). In order to see clearly at near, one must increase the power of the lens; this is known as *accommodation*. The parasympathetic impulse to the ciliary muscle constricts the circular part of the muscle, the zonular fibers then slacken, and the elastic capsule of the lens makes it more spherical thereby increasing its dioptric power. Accommodation decreases with age; by the mid forties, most aviators will be presbyopic and need spectacles to view clearly the panel, charts, and radios. Also of importance is that the eye is in focus for monochromatic yellow only, being hypermetropic for red and myopic for blue (2).

The retina is the innermost photosensitive layer. The neurosensory retina consists of ten layers. The light-sensitive elements are the rods and cones (Figure 14-3). The rods serve vision at low levels of illumination (scotopic vision) whereas the cones are effective both for medium and high levels of illumination (mesopic and photopic vision) and for color vision. The cones are mainly concentrated in the fovea centralis where the density has been measured at 47,000 cones/mm^2. The optic disc or blind spot is located



1. Visual axis
2. Cornea
3. Anterior chamber
4. Iris
5. Schlemm's canal
6. Posterior chamber
7. Vitreous
8. Medial rectus muscle
9. Sclera
10. Choroid
11. Retinal vessels
12. Central retinal vessels
13. Ciliary artery and nerve
14. Optic nerve
15. Fovea centralis
16. Vortex vein
17. Retina
18. Lateral rectus muscle
19. Lens
20. Ciliary zonule
21. Ciliary muscle
22. Angle of anterior chamber
23. Pupil



1. Anterior chamber
2. Iris sphincter muscle
3. Iris dilator muscle
4. Lens epithelium
5. Anterior lens capsule
6. Lens nucleus
7. Zonular fibers
8. Posterior lens capsule
9. Ciliary epithelium
10. Ciliary muscle (Circular)
11. Ciliary muscle (Radial)
11. Ciliary muscle (Meridional)
13. Angle of anterior chamber
14. Aqueous vein
15. Trabecular meshwork
16. Canal of schlemm
17. Sclera
18. Corneal stroma

FIGURE 14-1 Anatomy of the eye.

15 degrees nasal to the fovea and covers an area of 7 degrees in height and 5 degrees in width (Figure 14-4).

The vitreous, a clear colorless gel-like structure, fills the posterior four fifths of the globe. The vitreous is 99.6% water. The complaint of vitreous floaters is universal and usually innocuous. Floaters are usually due to the collapse of the protein/collagen scaffolding, thereby thickening and casting a shadow on the retina. More ominous floaters, which should be investigated at once, are often referred to as a *shower* of floaters; these are probably red blood cells. A dark floating membrane should be investigated for the possibility of a retinal detachment.

Adnexa

The adnexa of the eye are the extraocular muscles, the eyelids, and the lacrimal apparatus (Figure 14-5). There are six extraocular muscles attached to each globe, and because of the strong desire for fusion and the maintenance of single binocular vision both foveas are directed on the object of regard by both reflex and voluntary action. The lacrimal gland is located in a bony fossa on the frontal bone. It secretes the aqueous portion of the precorneal tear film. The corneal epithelium is covered by a three-layered film composed of an outer oily layer derived from the meibomian glands of the tarsal plate, the middle aqueous layer from the lacrimal gland, and the inner mucoid layer that arises from the goblet cells of the conjunctiva. The drainage system for tears consists of a small punctum or opening in the innermost edge of the upper and lower lids near the caruncle. These openings lead into a common canaliculus then into the lacrimal sac, exiting under the inferior turbinate in the nose.

The eyelids provide protection for the cornea, blinking six to eight times per minute; this blink also enhances the optical qualities of the cornea. The eyelids are closed by action of the

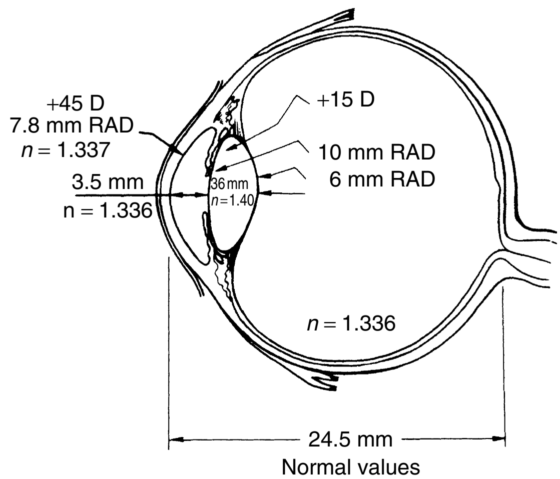


FIGURE 14-2 The normal values for the optical properties of the eye. RAD, radius; D, diopter; n, index of refraction.

orbicularis oculi muscles, which are innervated by the facial nerve (cranial nerve VII), and are opened by the levator palpebrae superioris muscles, innervated by the oculomotor nerve (cranial nerve III), elevation of the lids is assisted by Müller's muscle innervated by the sympathetic nervous system. Reduction of sympathetic tone to Müller's muscle can bring on the droopy eyelids seen on long, exhausting missions.

VISUAL PRINCIPLES

Vision is essential in all phases of flying and is most important in the identification of distant objects and in perceiving details of shape and color. The visual sense also allows the judgment of distances and gauging of movements in the visual field. In flying modern aircraft and spacecraft, near vision is also exceedingly important because it is absolutely necessary to be able to read the instrument panel, radio dials, charts,

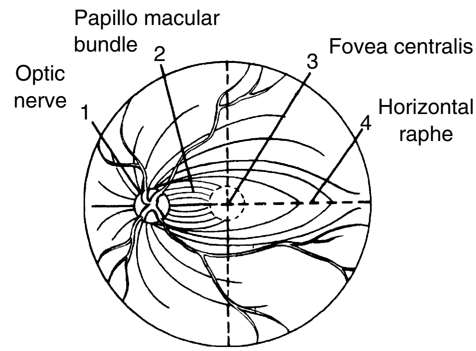


FIGURE 14-4 Fundus of the eye.

visual displays, and maps. At night, although one's vision is reduced, one must still rely on vision to safely fly the aircraft.

Physical Stimuli

The electromagnetic spectrum extends from the extremely short cosmic rays with wavelengths on the order of 10^{-16} m to the long radiowaves several kilometers in length (Figure 14-6). The part of the spectrum that stimulates the retina is known as *visible light* and extends from 380 nm (violet) to approximately 760 nm (red). A nanometer is a millionth of a millimeter, or 1×10^{-9} m. Adjacent portions of the spectrum, although not visible, affect the eye and are, therefore, of interest. Wavelengths of 380 nm and shorter, down to 180 nm, are known as *ultraviolet* or *abiotic rays*. Exposure of the eyes to this portion of the electromagnetic spectrum produces ocular tissue damage; the severity of the damage depends on the intensity and duration of exposure. Wavelengths longer than 760 nm, up to the microwaves, are known as *infrared* (IR) or *heat rays*. These rays, too, may cause ocular tissue damage, depending on the intensity and exposure time. The light intensity in extraterrestrial space above 30,000 m is approximately 13,600 footcandle (ft-c). At 3,000 m on a clear day, the light intensity is approximately

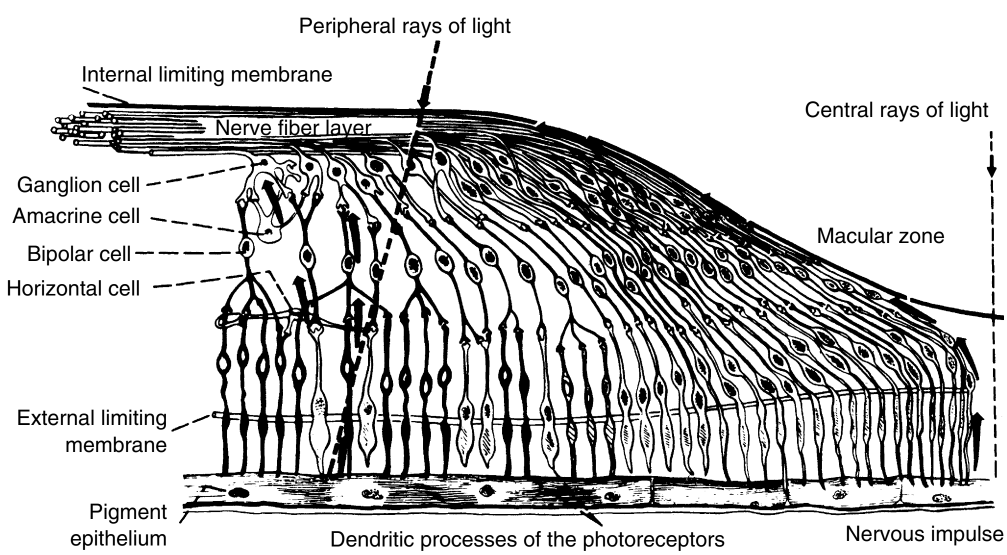
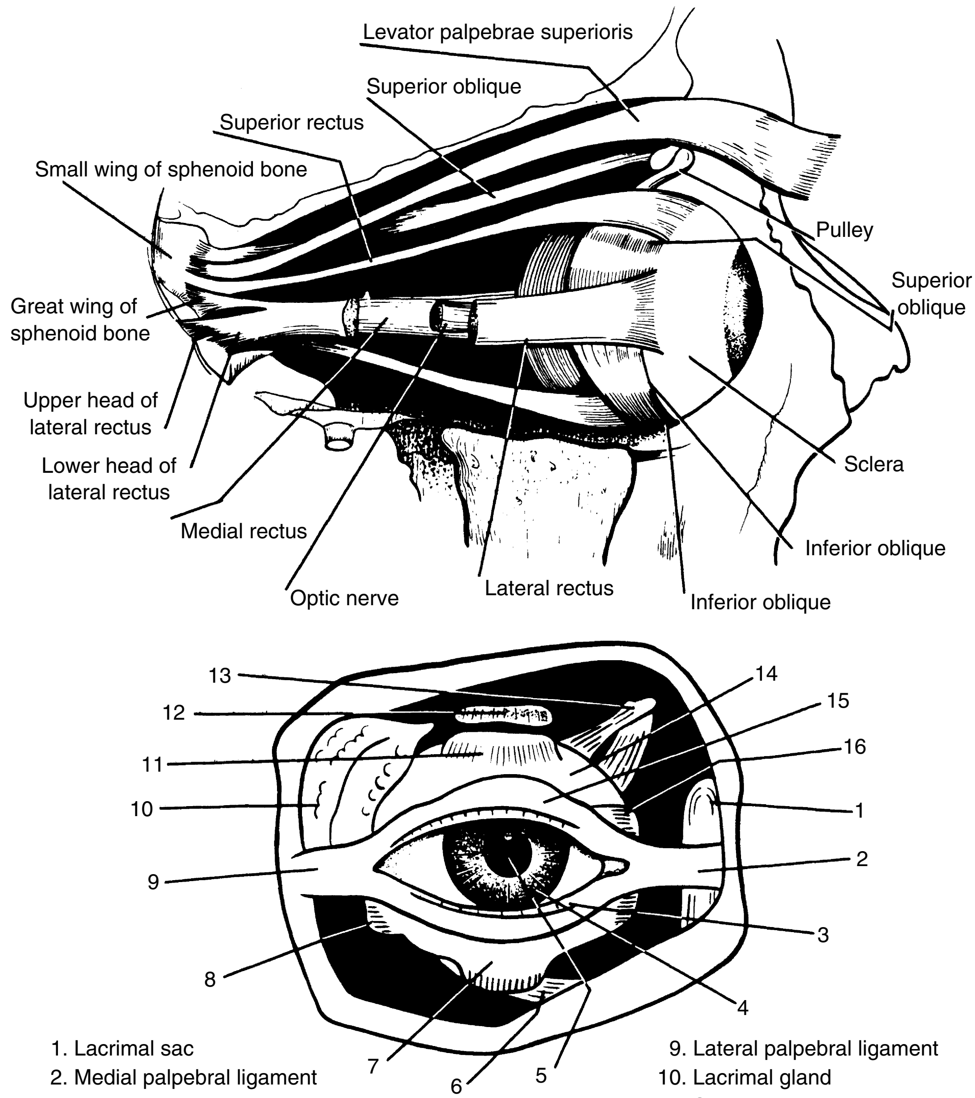


FIGURE 14-3 The retina.



1. Lacrimal sac
2. Medial palpebral ligament
3. Meibomian gland openings
4. Iris
5. Pupil
6. Inferior oblique muscle
7. Inferior rectus muscle
7. Lateral rectus muscle
9. Lateral palpebral ligament
10. Lacrimal gland
11 .Superior rectus muscle
12. Levator superioris muscle
13. Superior oblique muscle
14. Sclera
15. Eyelid
16. Medial rectus muscle

FIGURE 14-5 Ocular adnexa.

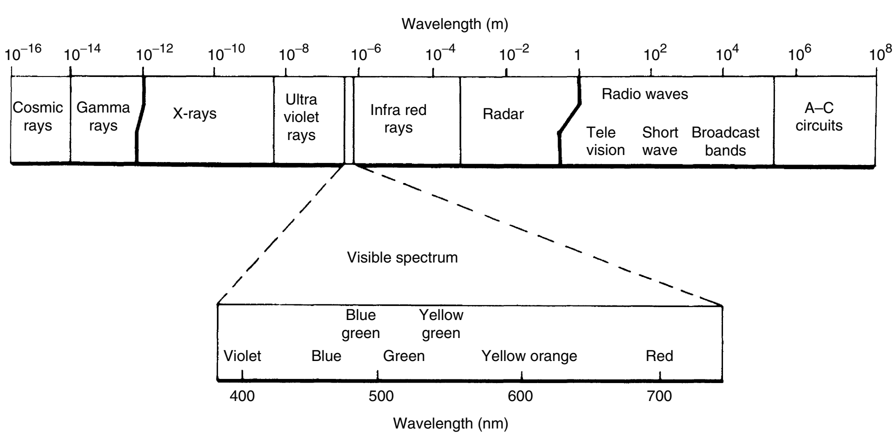


FIGURE 14-6 Electromagnetic spectrum.

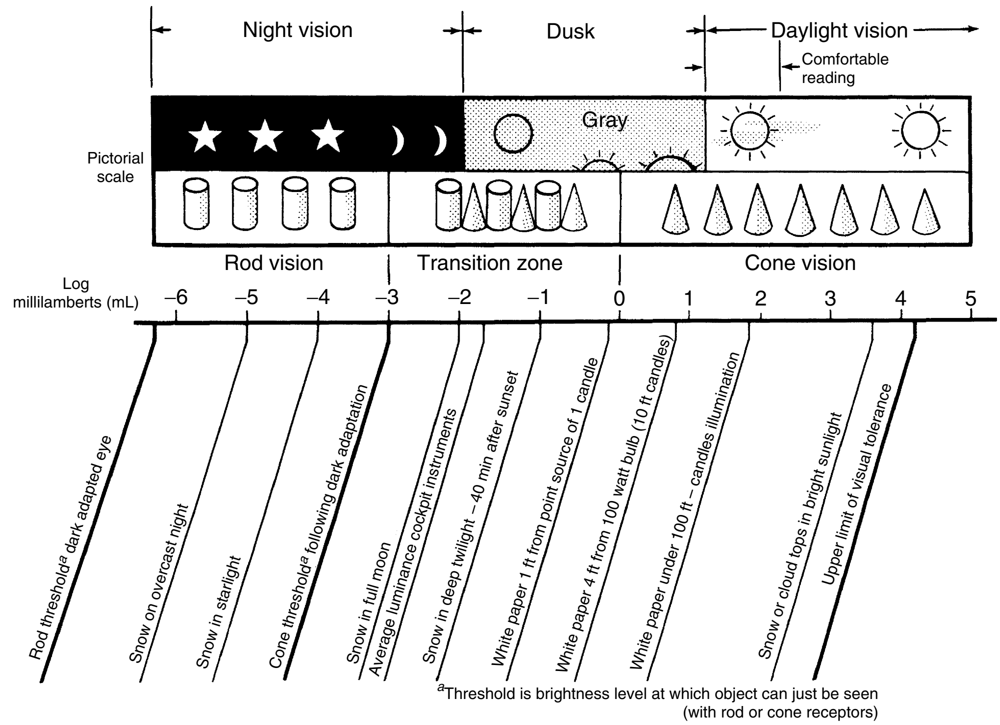


FIGURE 14-7 Luminance under varying conditions of illumination.

12,000 ft-c and approximately 10,000 ft-c at sea level. Water vapor, dust particles, and air in the atmosphere absorb some of the sun's light; in addition, selective absorption occurs. Ultraviolet light shorter than 200 nm is absorbed by dissociated oxygen. Ultraviolet light 200 to 300 nm is absorbed by the ozone layers in the atmosphere; this is fortunate because wavelengths 200 to 300 nm are the most damaging to the eye. These wavelengths produce the actinic keratoconjunctivitis that welders have when they fail to wear protective lenses. These wavelengths of 200 to 300 nm are no problem until an altitude of approximately 40,000 m is reached. This is approximately the height of the second ozone layer. Above this altitude, these ultraviolet wavelengths must be considered. Recent work done in the space program shows that the most abiotic rays have a wavelength of 270 nm (3). They must be filtered by protective visors, or they will severely limit the time that can be spent in extravehicular space activities. The rays that reach the earth, therefore, are 300 to 2,100 nm in wavelength, with an intensity varying between 10,000 ft-c at ground level to approximately 13,000 ft-c at presently attainable altitudes.

Visual Functions

The visual apparatus, stimulated by light, must primarily perform three basic functions. It must be able to perceive an object by the detection of light emitted or reflected from it; this is known as *light discrimination*. Second, it must be able to perceive the details of an object; this is known as *visual acuity*. Third, it must allow one to judge distances from objects and to perceive movement in the field of vision. These latter two functions combined are known as *spatial discrimination*. Obviously, all of these functions are perceived simultaneously; however, in this chapter, they will be discussed separately. Light discrimination consists of brightness sensitivity, which is the ability to detect a dim light; brightness discrimination, which is the ability to detect a change or difference in the brightness of light sources; and color discrimination, which is the ability to detect colors. As noted in Figure 14-7, when the illumination is below a certain intensity, approximately 10^{-6} log mL, the eye does not respond and there is total darkness. As the level of illumination increases, one begins to see shapes and objects; this is rod or scotopic vision. At best, this vision is on the order of 20/200 to 20/400 in scope. As illumination increases, such as with snow in full moonlight of 10^{-2} log mL, the threshold for the cones is reached, and this is known as *mesopic vision*; here, both rods and cones are functioning. A further increase in illumination (such as with white paper under 100 ft-c, equivalent to approximately 10^{2} log mL, causes the cones alone to be functional; this is known as *photopic vision*. The cones are now sensitive to color, and minute details can be appreciated. Increasing the illumination beyond 10^{2} log mL does little to enhance visual efficiency. The upper limit of tolerance for normal vision is 10^{4} to 10^{5} log mL of luminance. This would be equivalent to staring at the sun or at the detonation of a nuclear weapon. The eye can adapt to this tremendous range of illumination because of the dual system of rods and cones in the retina. The rods contain the photosensitive pigment rhodopsin and are sensitive to minute quantities of light energy. They are also sensitive to motion but not to color. The cones contain photosensitive pigments with maximum

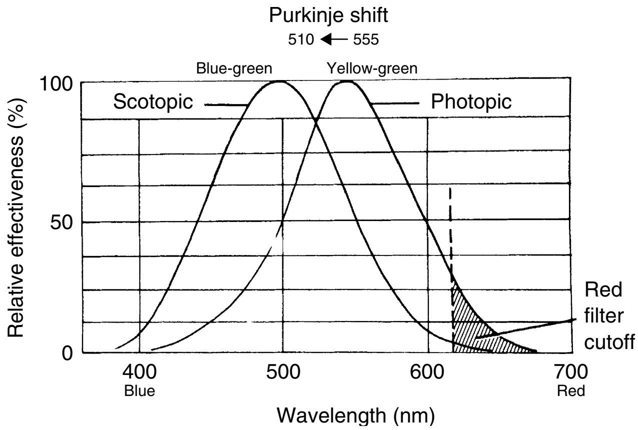


FIGURE 14-8 Luminosity curves for scotopic (rod) and photopic (cone) vision.

absorption at 445 nm (blue), 535 nm (green), and 570 nm (red). The cones must have much more light energy than the rods to be stimulated; however, the cones can perceive fine detail and discriminate colors.

The three psychologic components to color are hue, saturation, and brightness. Hue is the component denoted by naming a color, such as red, yellow, or orange. This is closely related to the wavelength of the light. Saturation refers to adding white light to the pure color so as to decrease the saturation of this color. For instance, a spectral red becomes pink when it is mixed with white light. The hue is still red, but its saturation has now been decreased. Finally, brightness relates to the amount of luminous flux reaching the eye. In essence, a source of high intensity or luminance seems brightly colored, for example, bright red or bright yellow, whereas a source of low intensity or luminance appears dark or dull colored (4).

At night or under low levels of illumination, the fovea, containing all cones, becomes a relative blind spot. Therefore, best vision is attained at night by looking 15 to 20 degrees off-center to utilize the part of the retina containing both cones and rods. As is noted in the dark adaptation curve (Figure 14.11), the cones adapt quickly, taking 6 to 8 minutes; however, the rods are much slower in adapting, requiring another 20 to 30 minutes in the dark. Rods and cones also have different peak sensitivities. The relative luminosity curves of photopic and scotopic vision show that scotopic vision (rod function) peaks at 510 nm, whereas photopic vision (cone function) peaks at 555 nm, as shown in Figure 14-8. The difference in these peak sensitivities is the basis of the Purkinje shift. The luminosity curves also show why red filter goggles with a cutoff at 610 nm allow the cones to receive enough light for the individual to function, while greatly reducing the light to the rods and allowing dark adaptation to take place.

The second of the basic functions, visual acuity, is the ability to see small objects, to distinguish separate details, or to detect changing contours. This is usually measured in terms of the reciprocal of the visual angle subtended by the detail. Central (foveal) visual acuity is high, whereas peripheral visual acuity is poor, less than 20/200. The retinal distribution pattern of rods and cones causes this difference in visual acuity, as shown in Figure 14-9. The cones are dense in the foveal and macular areas and even have a 1:1 nerve fiber-to-brain relationship in the fovea, whereas images outside of the macular area lose detail, becoming worse in the peripheral retina. In certain areas of the peripheral retina, many hundreds of rods may be connected to a single nerve fiber. This is an excellent system for picking up a minimum of light energy or detecting motion but poor for perceiving detail. Visual acuity is influenced by the refractive state of the eye. Visual acuity can be separated into four basic types: minimum visible, which is the ability to see a point source of light, with intensity determining whether it can be seen or not; minimum perceptible, which is the ability to see small objects against a plain background, where size (the angle subtended) and contrast become the determining factors; minimum separable, which

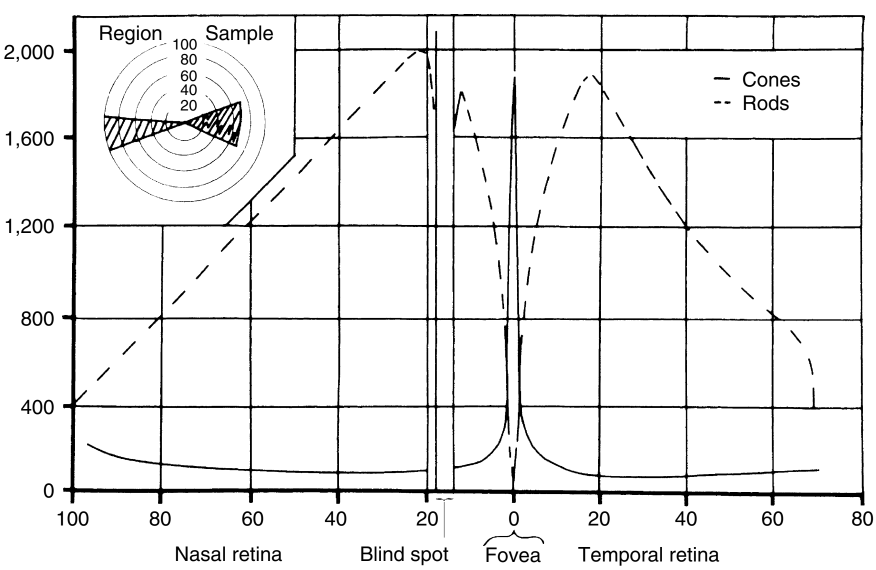


FIGURE 14-9 Rod and cone density in the retina. (Adapted from Chapanis RN. *Vision in military aviation*. Technical Report 58–399. Wright Field: Wright Aeronautical Development Center, 1958.)

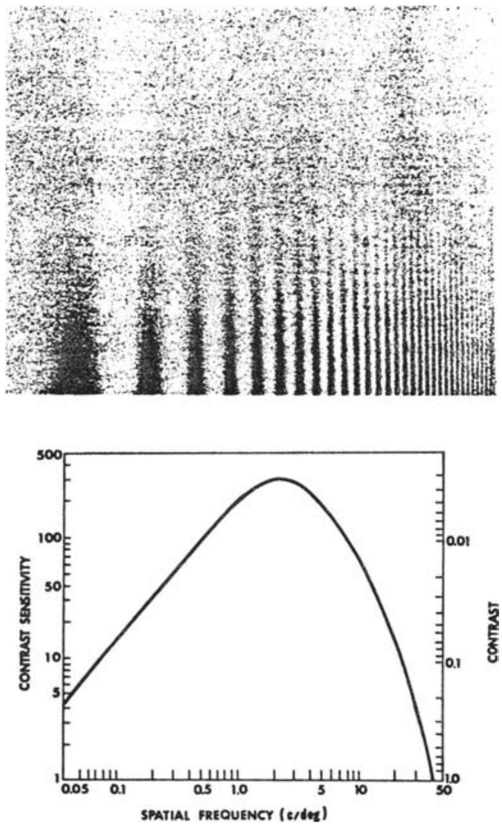


FIGURE 14-10 Contrast-sensitivity function. Upper half of figure: viewing, the sine gratings shows the effect of contrast and spatial frequency on visual resolution. Lower half of figure: normal contrast-sensitivity curve.

is the ability to see objects as separate when close together (also known as *two-point discrimination*); and minimum distinguishable, which is the form sense, usually measured on the Landolt C or Snellen charts and resolving 1 minute of arc break in the C or thickness in letters at 20/20 visual acuity.

Another form of testing visual resolving power is by the use of contrast sensitivity and gratings (Figure 14-10). The most useful form for visual testing is the sine form. The use of this sinusoidal form allows the ready application of a powerful mathematical tool, the Fourier transform. A sine grating of 30 cycles/degree visual angle may be compared with 1 minute of visual angle or 20/20 Snellen equivalent. A contrast sensitivity plot shows that the human visual system is most sensitive in the area of 2 to 4 cycles/degree (5). This method of testing may show reduced contrast sensitivity in conditions such as amblyopia, multiple sclerosis, optic neuritis, cataract, and possibly glaucoma.

Presently, this testing procedure has more value in the examination and evaluation of aircrew with ocular disease, unexplained visual loss, and research purposes (6).

The third important visual function necessary for aerospace flight is depth perception. This is the judging of distance and the perception of motion in the visual field. Distance judgment, or depth perception, is the ability to judge absolute distance or, more commonly, the relative distance of two or more objects. It is aided by conscious and subconscious cues learned from experience, such as aerial perspective, relative motion, relative size, distribution of light and shadow, overlapping contours, and, perhaps the most important of these monocular factors, motion parallax.

The binocular factors of convergence and stereopsis are also involved in this process. Stereopsis, resulting from the disparity of images on the retina of the two eyes, is the most important factor in judging the distance of near objects. In flying aircraft, however, maximum practical limit of stereopsis is believed to be only 200 m (600 ft).

Vision is a complex physiologic and psychological process that necessitates a decoding or interpretation of signals coming from the sensor (the eye) to the brain. Environmental stresses may disrupt the delicate physiologic balance necessary for maintaining clear vision and are discussed in ensuing sections.

VISION IN THE AEROSPACE ENVIRONMENT

The aviator and astronaut function in a hostile environment. In this section, the effects of this environment on the eye and vision are discussed. Some of the factors affecting vision include hypoxia, decompression, glare, high-speed acceleration, and, if one were to proceed into space, excessive electromagnetic energy, zero gravity, and other factors. All of these factors can degrade vision and, therefore, one's ability to perform duties at the most effective level possible.

Environment and the Eye

Hypoxia

Vision is the first of the special senses to be altered by a lack of oxygen, as evidenced by diminished night vision. The extraocular muscles become weakened and incoordinated and the range of accommodation is decreased, causing blurring of near vision and difficulty in carrying out near visual tasks. From sea level to 3,000 m is known as the *indifferent zone* because ordinary daytime vision is unaffected up to this altitude; however, slight impairment of night vision occurs such that all combat crews flying at night should use oxygen equipment from the ground up. From 3,000 to 5,000 m is the zone of adaptation. Some impairment of visual function occurs; however, this impairment can be overcome sufficiently for duties to be performed. At this altitude, retinal vessels become darker and cyanotic, arterioles show a compensatory increase of 10% to 20% in diameter, retinal blood volume increases up to four times, retinal arteriolar pressure, along with systemic blood pressure, increases slightly, the pupil constricts, and, at 5,000 m, a loss of approximately 40% in night vision occurs. Accommodation and convergence decrease, and one's ability to overcome heterophorias decreases. All of these changes can return to normal when the flyer returns to ground level or uses oxygen. Physiologic compensatory reactions enable flyers to perform normal tasks unless they remain at this altitude for long periods without oxygen. The zone of inadequate compensation is 5,000 to 8,000 m, so-called because the physiologic processes can no longer compensate for the lack of oxygen. The visual disturbance described above becomes more severe, with reaction time and response to visual stimuli becoming sluggish. Heterophorias can no longer be compensated for and become heterotropias with double vision. Accommodation and convergence are so weakened as to cause blurred vision and diplopia. Night vision is most seriously impaired. Once again, if one were not subjected to too long a stay at this altitude, all changes would be reversed by the use of oxygen or a return to sea level. Above 8,000 m is the zone of decompensation, or lethal altitude. Circulatory collapse occurs, with loss of vision and consciousness, and permanent damage to the retina and/or brain may result from the lack of circulation and hypoxia. Commercial aircraft and other aircraft with pressurized cabins maintain cabin-equivalent pressures of lower or equal to 2,500 m pressure altitude. None of the aforementioned visual effects is felt at this altitude except for an almost immeasurable effect on night vision. For smokers, the altitude zones can be considerably lower due to the effects of carbon monoxide (7).

Reduced Barometric Pressure

Decompression sickness is a disturbance that affects the flyer as a result of reduced barometric pressure. Infrequently with decompression sickness, a transitory visual defect consisting of homonymous scotoma or even hemianopia may occur, followed by headache that closely resembles migraine. Even more rarely, the aviator may be afflicted by transitory hemiplegia, monoplegia, aphasia, and disorientation. In rare cases, permanent visual impairment occurs. See Chapter 3 for further detail and discussion of decompression sickness.

Visual Environment

The aviator's visual environment is constantly changing. One travels from night to day, from sunlight to shadow, from well-structured scenes to empty visual fields. Fortunately, the eye is quite adaptable, functioning in light levels from 1×10^{-6} log mL to 1×10^{5} log mL. For example, the brightness of the full sun on a cloud is approximately 6×10^{3} log mL, snow in full moonlight is 1×10^{-2} log mL, and snow in starlight is 1×10^{-4} log mL. As higher altitudes are attained, the sky darkens, being lighter at the horizon and darker at the zenith. This reverses what is considered normal light distribution, creating a bright view below and darkness above. At high altitudes, less haze is evident and the sun's rays are much more intense, so that 13,600 ft-c of illumination occurs at 30,000 m. A higher proportion of ultraviolet rays are also found at this altitude. For each kilometer (3,300 ft) increase in altitude, ultraviolet radiation increases by approximately 6%. Glass sunglass lenses decrease the intensity of light and protect against ultraviolet radiation as well. Plastic spectacle lenses must have attenuators in the plastic to filter out ultraviolet radiation. Newer materials, however, such as polycarbonate, being used in the windscreens of modern aircraft substantially reduce the amount of ultraviolet radiation that enters the cockpit. This material cuts off most of the ultraviolet light below 380 nm. The aviator's vision is also affected by the lack of detail in the sky at altitude. This empty field, or space myopia, causes a decrement in his visual capabilities. Finally, changes occur in the appearance of sunlight and areas of shadow. Areas in shadow are illuminated by scattered light, but less light scatter and brighter sunlight occur at high altitude, so that the contrast between the sunlit and shadowed areas increases.

Visibility

Much of modern flying is done in the cockpit. This necessitates good near vision and is dependent on having an adequate amount of visual accommodation. In spite of instruments and radar scopes, one must still see outside the cockpit to land and take off, fly formation, navigate, and, especially, watch for other aircraft. Multiple related factors allow the aviator to see objects in the environment (1): the size of the target, which is relative to its distance (2); the luminance or overall brightness (3); the degree of retinal adaptation (4); the brightness and color contrast between the target and background (5); the position of the target in the visual field (6); the focus of the eye (7); the length of time the object is seen; and (8) atmospheric attenuation.

The visibility of an object depends mostly on its size and contrast with the background. In daylight, with the best of contrast (a black object on a white background), an object would be seen at near the threshold of visual acuity, subtending 0.5 minute of arc, or the equivalent of 20/10 (Snellen) vision. A speck of light against a black background, such as a star, can be seen even when it is much smaller and obviously at enormous distances; however, this example is not a function of visual acuity but only of light perception. A star appears bigger because it is brighter not because it subtends a larger visual angle. The visibility of objects is lost as the contrast is reduced between the object and its background. In such a case, the object, now with lower contrast, must be much larger or nearer before it can be seen. In conditions of haze or mist, such a marked loss of contrast exists that even a large object may not be seen at all. Testing techniques, such as contrast sensitivity function tests, hold promise for the identification of individuals whose systems function more effectively at lower contrast thresholds. The visibility factors outlined in the preceding text are, to a certain extent, interrelated, so that a reduction in one may be compensated for by an increase in one of the others. For instance, an object may be so small or so far away that it is just below the threshold of visibility. It may be made visible by an increased illumination or by improving the contrast between it and its background or both. In other instances, the object may be better perceived when more time is spent viewing it.

Targets in the periphery of the visual field must be proportionally larger to be seen. To get maximum visibility, the target will have to be seen within 1 degree of fixation (fovea). When the object in the peripheral field is moving, it is easier to detect.

One final factor capable of degrading target acquisition is empty field or space myopia. Older theories explained that the resting state of the eye was one of zero accommodation. More sophisticated testing techniques (laser optometer) show that in some individuals, the resting state of the eye is actually one in which a small amount of accommodation is exerted, thereby defocusing the eye for distance vision. In the so-called resting states, these individuals have 0.75 to 1.00 D of myopia thereby degrading their distance visual acuity because their resting focus is 1 to 1.5 m distant from the eye. This is said to occur in both emmetropic and myopic individuals. Moderately farsighted individuals (hypermetropes), however, may find that this accommodative tonus is actually advantageous and that their distance vision perhaps may be enhanced. In bright daylight, the small pupil produced compensates somewhat for the space myopia by increasing the depth of field; however, a better method of overcoming this induced myopia is to fix on a distant object. Actually, anything more distant than 15 to 18 m helps to relax the accommodation sufficiently to improve the distance visual acuity. Night myopia, which is similar to empty field and space myopia, is discussed in the following section on night vision.

Night (Scotopic) Vision

Night vision is extremely important in aviation. It is quite different from day (photopic) vision. The eyes must be used differently at night for the aviator to gain maximum usefulness of vision. The aviator must understand the principles of night vision and must practice using the eyes at night to gain efficient vision at night.

Not all parts of the retina are alike in their reaction to light. A small, central area containing only cones is responsible for maximum visual acuity and for color discrimination, but it fails to operate under low intensities of illumination. This is the fovea, the area with which one reads and where one focuses objects in the direct line of vision. It gives us central vision, which is useful in high and moderate illumination (photopic and mesopic conditions).

In the remaining peripheral area, both the rod-type and cone-type receptors are present. The peripheral retina is capable of less acute visual perception and of only poor color determination, but it functions under low illumination or scotopic conditions. According to the widely accepted duplicity theory of vision, the human eye is an eye within an eye. Central vision requires light of approximately 1×10^{-3} log mL intensity or greater. Bright moonlight gives approximately 1×10^{-2} log mL. Hence, in light that is less intense than moonlight, little central vision is evident. Peripheral vision requires only one-thousandth as great an intensity 1×10^{-6} log mL or more. On a dark, starlit night, the individual sees only with the peripheral area of the retina. This explains why pilots often complain that they are able to see an aircraft at night only to have it disappear when they look directly at it. To keep an object in sight at night, one must learn to look off to the side at approximately a 15- to 20-degree angle. When the light intensity is between 1×10^{-3} and 1×10 degrees log mL, both the rods and cones are functioning, and mesopic vision occurs (Figure 14-7).

Individuals can determine which type of vision they are using by noting whether they have color sense. The cones perceive all colors. Rods pick up colors only as shades of gray. Most of the cones are in the central area of the retina, so that if colors were recognized at night, one would have central vision; however, if everything were to appear in shades of gray, one would only have peripheral or rod vision.

Dark adaptation is the process by which the eye adjusts for maximum efficiency in low illumination. It is commonly experienced when one first enters a theater or walks into darkness from a brightly lit room. The central area of the retina dark-adapts in approximately 6 to 8 minutes, but this part of the retina is useless for night vision. The peripheral area dark-adapts in approximately 20 to 30 minutes, although further slight adaptation continues over a period of 2 days (Figure 14-11). This peripheral area is not sensitive to dark-red light (630 nm or longer in wavelength). Such light is not perceived even as gray, so dark adaptation occurs in the periphery in dark-red light as though no light existed. This characteristic is fortunate because, by wearing red, light-tight goggles before a flight, pilots can read or rest in a brightly lit room while the peripheral areas of their retinas are dark-adapting.

Dark adaptation is an independent process in each eye. It is slow to develop in the dark and is quickly lost in the light. The aircrew must be so familiar with the location of their equipment and controls that lights are unnecessary for making adjustments in flight. The aviator should avoid gazing at exhaust stacks or any other bright light sources. When using light at night in the plane, such as in reading instruments, maps, or charts, as little light as possible should be employed and for as brief a time as possible, and red light should be used; however, red lighting does create problems, such as accommodative fatigue and reduction of color perception. Therefore, red light is no longer favored for cockpit visual activities. When an individual who is exposed to bright light closes one eye, the closed eye remains dark-adapted, although the exposed retina of the open eye has been bleached.

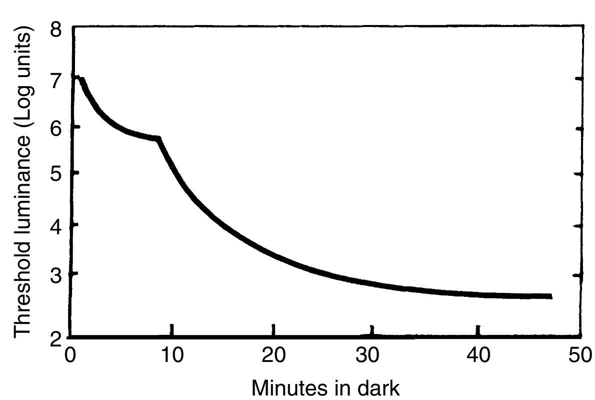


FIGURE 14-11 Dark-adaptation curve.

Dark adaptation also depends on an adequate supply of vitamin A in the diet. Vitamin A is found in vegetables that are green or were green at some stage of development, such as lettuce, carrots, cabbage, peaches, tomatoes, green peas, and bananas. Other sources of vitamin A include milk, eggs, butter, cheese, and liver. A deficient diet or an illness that decreases the vitamin A supply impairs night vision and a return to normal vision may take several months, even when large doses of vitamin A are ingested. Excessive vitamin A ingestion, such as taking in large doses of vitamin capsules, is worthless to a normal person. Various drugs have also been studied and have not been found to improve a normal person's dark adaptation.

Without supplemental oxygen, the average percentage decrease in night vision capability is 5% at 1,100 m altitude, 18% at 2,800 m, 35% at 4,000 m, and a 50% decrease in night vision capability at 5,000 m altitude. Lack of oxygen, fatigue, and excessive smoking all reduce the ability to see well at night. For military flying, oxygen should be used from the time of takeoff for maximum visual acuity. Fatigue should be prevented, insofar as possible, by obtaining adequate sleep before flying. Hypoxia resulting from carbon monoxide poisoning affects brightness discrimination and dark adaptation in the same way as altitude-induced hypoxia. As an example, 5% saturation with carbon monoxide has the same effect as flying at 3,000 m without oxygen. Smoking three cigarettes before a flight may cause a carbon monoxide saturation of 4%, with an effect on visual sensitivity equal to an altitude of 2,800 m or a 15% to 18% decrease in night vision.

During World War II, much work was done on the use of red cockpit illumination. The use of a red light having a wavelength greater than 630 nm illuminating the cockpit is desirable from the viewpoint of dark adaptation. The intent was to retain the greatest rod sensitivity possible while permitting an effective illumination for foveal vision; however, with the increasing use of electronic devices for navigation, the importance of the pilot's visual efficiency inside the cockpit has increased markedly. Therefore, low-intensity white cockpit lighting is presently advocated because it affords a more natural visual environment within the aircraft without degrading the color of objects that are not self-luminous. The disadvantage of the previously used red lighting caused red markings on aerial maps to be invisible when viewed in this light. Red light also tends to create or worsen near-point blur in prepresbyopic, presbyopic, and, at times, hypermetropic pilots. Because of the chromatic aberration of the eye, humans are hypermetropic for red (8).

Ultraviolet light has been used for cockpit illumination and has a disconcerting side effect if it were to become reflected directly into the eye. These radiations produce a fluorescence of the crystalline lens in the eye, giving the pilot a sensation that he is flying in a fog. Properly adjusting the ultraviolet lamps and reducing their intensity can overcome this fluorescence problem to some degree. Radiations from these lamps are not injurious to the eyes because, even at highest intensity, they are still far below the threshold for affecting the corneal epithelium.

During World War II, the problem of night vision was studied intensively by numerous scientists, but no single, satisfactory test of night vision was developed. The United States Air Force (USAF) did develop the radium plaque night-vision tester, which is a self-illuminating Landolt C target; however, because it contains radium, it is rarely used now (9).

At present, the best test of night vision is the Goldmann-Weekers Dark Adaptometer. This instrument is capable of determining the dark-adaptation curve of an individual with great detail and accuracy. It is obviously not something that should be done on everyone because it is time-consuming, the apparatus is expensive, and is available only in research institutions and larger clinics. With this instrument, one can establish the threshold of night vision in an individual. The testing results in the familiar dark-adaptation curve (Figure 14-11).

NIGHT-VISION GOGGLES

Modern technology has also introduced night-vision goggles (NVGs), which enhance vision at night over and above that possible by the naked eye (Figure 14-12). Currently available NVGs can intensify ambient light to approximately 1,000 times (×1,000). Several electro-optical devices are available to improve vision at night, including NVG and forward-looking infrared (FLIR) systems. Most NVG systems are helmet mounted and look like binoculars. To make objects and landscape visible at night, NVGs usually employ two image-intensifier tubes to amplify or intensify low levels of reflected and emitted ambient light. Image-intensifier tubes are sensitive to some visible and short-wave IR radiation, but a minimum amount of ambient light is needed to excite the green phosphor screen and produce visible images.

The NVG-intensified image resembles a black and white television image except that it is in shades of green instead of in shades of gray, due to the selected display phosphor.

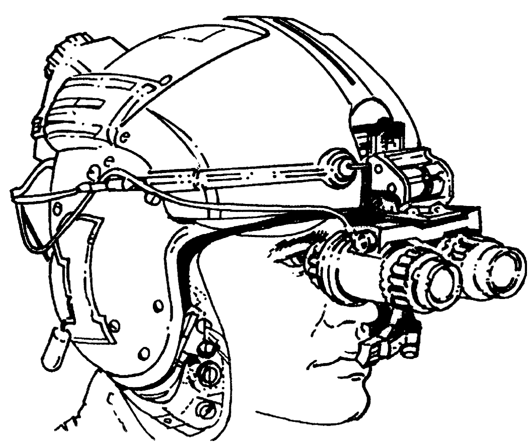


FIGURE 14-12 Anvis (III-Gen) Night-vision goggle.

The image that is seen by the aircrew member is not a direct view, but an image displayed on a phosphor screen. The NVG system is analogous to using a microphone, amplifier, and speaker to amplify a faint sound and make it audible. In both cases, some of the "natural fidelity" may be lost in the amplification process.

NVGs enhance night vision over unaided scotopic vision; however, they do have significant limitations. The performance limitations include visual acuity of approximately 20/40 at best, a field of view of 40 degrees or less, degraded depth perception, little or no stereopsis, and a different spectral sensitivity than the human eye. Therefore, training and experience with NVGs is critically important for flying safety.

A FLIR device consists of a cockpit-or helmet-mounted video monitor that displays picture from an internal IR sensor that is usually fixed forward (i.e., slaved to the nose of the airplane). These sensors are sensitive to the long wavelength IR (thermal) and provide excellent resolution. IR sensors can detect radiation in either the 3,000 to 5,000 nm or the 8,000 to 12,000 nm spectral range. A FLIR must have thermal radiation available, but many objects radiate measurable amounts of IR energy in the spectral range.

Electro-optical Design

A brief description of the operating principles of NVGs will make it easier to understand their workings and limitations. Ambient light entering the intensifier tubes is focused by an objective lens onto a photocathode. The schematic diagram of an intensifier tube is presented in Figure 14-13. When photons of ambient light strike the photocathode, which is sensitive to visible and near-IR radiation, electrons are released, creating a cascading effect. The number of electrons released from the photocathode is proportional to the number of photons striking it. The electrons are then accelerated and multiplied by a microchannel plate, which acts like a large array of photomicromultiplier tubes. The microchannel plate, approximately the size of a nickel, guides the accelerated electrons to a phosphor screen that produces an intensified light image. The light amplification is referred to as the *gain of the device*. The gain is the ratio of the light delivered to the eye by the phosphor screen to the light striking the objective lens. Modern NVGs have a gain of 400 to 1,000.

NVGs do *not* turn night into day. Although pilots are usually impressed the first time they look through NVGs, many complaints occur the first time they fly with them. Although it is true that visual function with NVGs is impressively enhanced over scotopic function in many ways, NVG performance is inferior compared to normal photopic function. The degradation in visual performance that NVGs impose must be emphasized to aircrew.

Much more detailed information on NVGs, operational issues, environmental considerations, and fitting techniques is explained in the publication, *Night Vision Manual for the Flight Surgeon* by Miller and Tredici (10).

SPATIAL DISCRIMINATION, STEREOPSIS, AND DEPTH PERCEPTION

In aviation, it is important to accurately localize in three-dimensional space. When this cannot be done, one becomes spatially disoriented, which is a marked hazard to the flyer. Under $+1\ G_z$ acceleration, one orients to the earth by proprioceptive impulses from various parts of the body, from receptors in the semicircular canals and vestibular apparatus, and with the strongest cue to orientation, the visual system. Linear and angular accelerations are capable of producing spatial disorientation, especially when outside visual reference is excluded; however, when adequate external visual references are available, spatial disorientation usually does not occur. The pilot's ability to resist spatial disorientation, then, is greatly enhanced by adequate visual references and is diminished by mental stress. The visual cues to the perception of depth are both monocular and binocular. The monocular cues are learned, and some investigators believe that they can be improved by study and training. These cues, however, are the ones that can be the most easily tricked by illusions. Conversely, stereopsis, which is the most important binocular cue, is innate and inescapable. When flyers have this capability, it remains with them, even when the learned

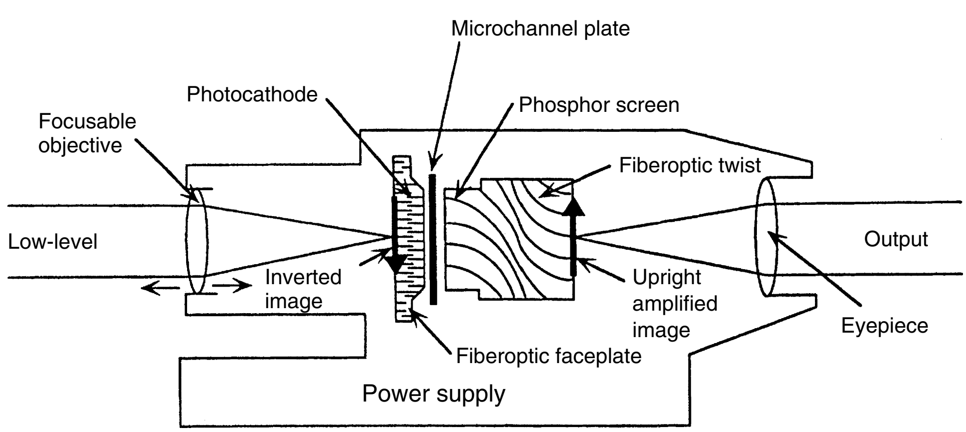


FIGURE 14-13 Photocathode tube schematic.

cues are sparse, such as at night, under conditions of low visibility, and in unfamiliar surroundings. Unfortunately for flyers, however, the maximum range at which their stereoscopic vision is useful is only up to 200 m. This is not to imply that stereopsis is required in flying an aircraft because numerous individuals who lack stereopsis still make good aviators; however, when the pilot does have stereopsis, so much the better. Therefore, stereoscopic testing procedures should be retained in the flight examination. The stereoscopic test for flying is probably the single most revealing component of the visual examination. Individuals who pass the stereoscopic test down to 15 to 20 seconds of arc must, of necessity, have well-functioning visual systems. They must have two eyes that are equally balanced: visual acuities must be excellent to attain this kind of arc disparity, they must have normal retinal correspondence, and their motility status must be functioning normally in at least the straight-ahead position. In essence, even if stereopsis had nothing to do with flying, retaining the stereopsis portion of the ophthalmologic examination is wise.

Depth Perception (Spatial Localization)

Depth perception is the mental projection onto visual space of a perceived object in real space. Correlation of the real object in real space with that projected in visual space results in accurate depth perception. Both monocular and binocular cues to depth perception exist.

The monocular cues are as follows:

1. Size of the retinal image (size constancy)—being able to judge the known and comparative size of objects is an important cue
2. Motion parallax—the relative speed of motion of images across the retina; objects nearer than fixation move against the observer's motion, distant objects move in the same direction as the observer's motion
3. Interposition—one object obscured from vision by another
4. Texture or gradient—detail loss at increasing distances
5. Linear perspective—parallel lines converging at distance
6. Apparent foreshortening—for example, a circle appears as an ellipse at an angle
7. Illumination perspective—light sources are usually assumed to be from above
8. Aerial perspective—distant objects appear more bluish and hazy than do near objects

The binocular cues are as follows:

1. Convergence—the value of this cue is questionable and is generally used only for near distances
2. Accommodation—also useful only for near distances
3. Stereopsis—this is the visual appreciation of three dimensions during binocular vision, occurring during fusion of signals from slightly disparate retinal points, which are disparate enough to stimulate stereopsis but not so disparate as to cause diplopia

The two most important monocular factors for flying are considered to be motion parallax and size of the retinal images. All monocular cues are derived from experience and are subject to interpretation. Stereopsis is believed to be the most important binocular cue and is based on a physiologic process that is innate and inescapable. Like visual acuity, stereopsis can be graded and is known as *stereo acuity*, which is measured in seconds of arc of disparity. Owing to the limiting factors such as the interpupillary distance, stereopsis is not reliable beyond 200 m (600 ft) (11).

Stereopsis (one element in the perception of depth) is measured by several different instruments. One can measure stereopsis for near distances, on the Verhoeff depth-perception apparatus, where stereo acuity is measured at 1 m without special optical devices. Stereopsis for near distances also can be measured by the Wirt (Titmus) circles. In this case, the eyes are dissociated with polarizing lenses. Stereoscopic vision for distance is measured in testing devices, such as the Bausch and Lomb Ortho-Rater, Titmus, Keystone, or Optec instruments. Using these instruments, separate images are presented to each eye, and lenses in the instruments project the images to infinity. In essence, these are tests of stereoscopic vision for distance, and many examiners are not aware that in some motility disturbances, such as microstrabismus, the candidate may have normal stereoscopic vision (depth perception) for near but not for distance or vice versa.

COLOR VISION

Aeromedical experts and flyers have emphasized the importance of normal color vision since World War I. In 1920, Drs. William H. Wilmer and Conrad Berens noted in their article, *The Eye in Aviation*, that the proper recognition of colors played an important part in the success of aviators (1). In modern aviation, both civil and military, color discrimination requirements have not diminished, but rather have expanded dramatically. For instance, aviators and aircrew must be able to identify assorted colored light signals and navigation lights, as well as the colors of various reflecting surfaces such as ground targets, flags, smoke, and flares. It is important to be able to identify colors used on maps and charts even in less than optimal lighting and, especially in the military, for ascertaining subtle color differences in targets and terrain. Modern aircraft now incorporate full spectral color in electronic flight information systems (EFIS) designed to speed up flight information to aircrew primarily because color increases efficiency without demanding further conscious effort. Under certain conditions, such as bright daylight, the color contrast of these displays decreases. With hypoxia and impoverished visual conditions, such as fog, smoke, haze, or in dim light, color perception degrades, with color defectives disproportionately degrading compared to normals under decreasing illumination, hypoxia, and fatigue (12–19). Chronic hypoxia at cabin altitudes between 8,000 to 10,000 ft above ground level (AGL), where supplemental oxygen has traditionally not been supplied, has emerged as an issue of concern, particularly in military operations. All of these factors place additional emphasis on an aviator having normal color vision than in the past.

Color vision deficiencies can be congenital, acquired, or induced artificially. Congenital color deficiencies are almost always red/green and are much more common in males, whereas blue/yellow defects affect both sexes equally and are rarely congenital, rather a result of ocular disease or toxicity. Congenital red/green defects are inherited as a sex-linked recessive trait. Approximately 10% of all males versus 0.5% of females are congenitally red/green color defective (20,21). Unlike sex-linked red/green color vision deficiencies, congenital blue/yellow defects are extremely rare, occurring equally in 0.001% to 0.007% of males and females (22,23). Acquired defects typically first present as blue/yellow deficiencies and are estimated to be present in 5% to 15% of the general population (24–28). As a result, identification of true color normalcy requires testing for red/green and blue/yellow defects, both congenital and acquired.

How much color deficiency is required for safe and effective flying remains under heavy debate, particularly in civil aviation. In July 2002, the National Transportation and Safety Board (NTSB) identified defective color vision as a contributing factor in the crash of a commercial aircraft in Tallahassee, Florida (29). As a consequence of that mishap, the NTSB recommended that the Federal Aviation Administration (FAA) reevaluate existing color vision requirements and adopt more effective testing methodologies. Consequently, there is no question that this accident and the proliferation of color in the modern cockpit mandates a fresh look at this relationship. For example, color defectives make more mistakes, take more time, and need to be closer to color-based targets when compared to color normals.

For most purposes, individuals with normal color vision can be effectively screened using pseudoisochromatic plates (PIPs). Few color normals will fail properly administrated PIP tests, whereas color abnormals will have great difficulty scoring like a normal, unless they have learned techniques to defeat these tests. In many cases, however, subjects with mild color vision deficits perform as poorly as those with deficiencies that are more significant. Lanterns, long used as secondary occupational tests since the 1800s, have fallen out of favor because of relative unavailability, lack of operational relevance in the modern environment, and other technical problems. For example, the color threshold test (CTT) developed at the Army Air Forces School of Aviation Medicine in World War II permitted mild color defectives to enter aviation training; however, the scores used for the CTT were based on field studies involving the ability to distinguish at the time between colored pyrotechnic flares, the biscuit gun, and wire coding schemes (30–33). It was eventually abandoned once replacement Wratten filters were no longer made. The U.S. Navy developed the Farnsworth lantern, or FALANT, during World War II for naval signalmen (34,35). It was designed to qualify 20% of color defectives, presumably mild defectives believed to be safe in the signal environment at the time, into Navy career fields that required "normal" color vision; however, it no longer remains linked to current operational requirements. Furthermore, recent studies have shown it to pass much more severe defects and its utility to reliably identify color normals for modern applications has been challenged, especially by the NTSB (36–47). Consequently, the USAF no longer uses it for color vision testing. In addition to assorted PIP tests, other tests of color vision such as Farnsworth's Dichotomous Test (Panel D-15) and FM-100 tests have been used for aviation. Many of these are effective in identifying dichromat subjects, but become unreliable in testing less severe color vision defectives. None is as effective as an anomaloscope based on Rayleigh and Moreland metameric equations. Recently devised tests based on spatiotemporal luminance masking, such as the color assessment and diagnosis (CAD) test, or those employing isolated cone-specific contrast principles, such as the cone color test (CCT), may even displace PIPs and anomaloscopes as more convenient and definitive screeners (48–53). Until then, the definitive gold standard color vision test against which all other color vision tests are compared is the anomaloscope (Table 14-1). The North Atlantic Treaty Organization (NATO)'s Working Group 24 (WG 24) recommended that color vision testing for modern aviation should involve an initial PIP test followed by an anomaloscope, if more definitive assessment is required (54). WG 24 also recommended abandoning use of all occupational lantern tests. However, all color vision tests that rely on reflected light, whether PIPs (Ishihara, Dvorine, AO, Hardy-Rand-Rittler, Igaku-Shoin, etc.) or hue discrimination tests (D15, Lanthony, FM100, etc.) must be presented with light of proper Kelvin temperature (Illuminant C). The most commonly used Illuminant C is the MacBeth light, with a temperature of approximately $6{,}000^{o}$K (13). All of these tests must also be properly administered, for example, given monocularly away from other light sources and applicable time limitations.

According to the Young-Helmholtz theory of color vision, three classes of cones are present in the primate retina. These cones absorb light with peak sensitivities of 445 nm (blue), 535 nm (green), and 570 nm (red), as shown in Figure 14-14. Modern terminology refers to them as *short* (S), *middle* (M), and *long* (L) wavelength sensitive cones. Any color of the spectrum may be constituted with varying

TABLE 14-1

Incidence of Color-Vision Deficiency

Males	*Percent*	*Females*	*Percent*
Protanopia	1.0	Protanopia	—
Deuteranopia	1.4	Deuteranopia	0.4
Protanomaly	0.78	Protanomaly	0.4
Deuteranomaly	4.6	Deuteranomaly	—
Total[a]	7.78	Total[a]	0.8

[a]Monochromatism occurs in 1/100,000 individuals.

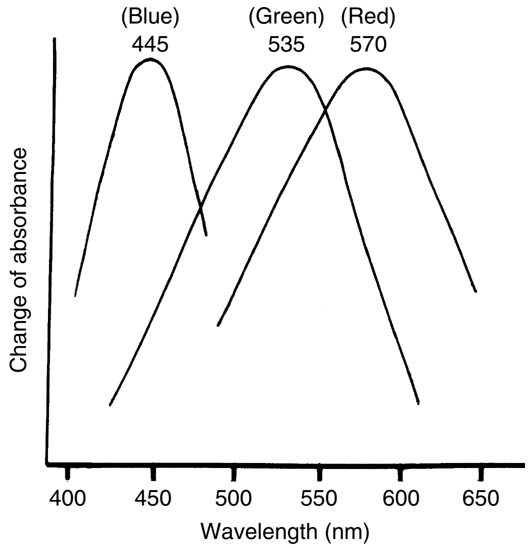


FIGURE 14-14 Cone-photosensitive pigments. Maximum absorption wavelengths.

combinations of these three primary colors, and when all three colors are stimulated, the color perceived is white.

The most severe color deficiency is known as *monochromatism*, a complete absence of color sensation. There are perhaps only 1:100,000 such individuals in the general population, and with central visual acuities in the 20/200 range, would never qualify for aviation. Colorblind individuals with only two cone types are called *dichromats* and constitute 2% of 3% of the males. Dichromatism includes protanopia (no L cones) in 1% of males, whose only color sensations are gray, blue, and yellow and who confuse reds with greens, blue-greens, and browns; deuteranopia (no M cones) also in 1% of males, whose only color sensations are gray, blue, and yellow and who confuses greens with reds, purples and browns; and tritanopia (no S cones) in those who do not see blues and yellows.

The vast majority of individuals with defective-color vision are color weak. These individuals are called *anomalous trichromats*. In red/green anomalous trichromats, the sensitivity curve of either the M or L cone shifts toward the other, resulting in neurologically distorted input and failure to respond to some visible wavelengths seen by color normals. Protanomaly, meaning "red-weak," results from a shift of the L cones and occurs in 1% of males. These individuals miss certain reds and require more red stimulation than normal to make an anomaloscopic color match. Deuteranomaly, meaning "green weak," results from shifted M cones occurring in approximately 5% of males. These individuals need more green stimulation to make anomaloscopic match. Tritanomaly results from shifted S cones and is a condition in which more blue or blue/green stimulation is required to make a color match.

Color vision defects can also be acquired from diseases, drugs, medications, intense lights, trauma, and other conditions that affect retinal cones, optic nerve fibers, and occasionally from direct brain injury. For example, early glaucoma may manifest unilaterally as a blue/yellow deficiency without impacting visual acuity, thereby making monocular color testing mandatory (55–68).

Since World War I, aircrew have been required to have normal color vision. Historical color vision testing strategies reflect red, green, and white signal and navigation light requirements in a male-dominated occupation at the time. Shape and other configurations were employed as secondary cues. Color use in modern displays exploits unique advantages in color normals to expedite information and improve situational awareness. Modern aviation, particularly military and air traffic control environments, increasingly employs multispectral color without noncolor redundancies. Merging input from diverse sensors, so-called sensor fusion and synthetic cockpit recreation of external scenes represents new technologic thrusts that will continue to challenge color perception in the future. Color vision defectives have well-known problems with EFIS displays regardless of degree of deficiency (69–78). Approximately 3% of males with congenital red/green deficiencies can be classified as mild, but regardless of degree, each color defective differs from another. Arguably, therefore, embracing color display designs that all color defectives can also use effectively, including dichromats, will degrade overall system capability by negating the efficiency of color usage.

Filter techniques have been advocated for decades to "cure" color-vision defects. For example, the "X-chrom lens," is a red, 15% to 20% transmitting-filter contact lens that is worn on only one eye. The lens was touted as the device to put individuals with defective color vision into the cockpit. Such lenses create a "new" color world to help defectives avoid their color confusion. However, other parts of that normal world are degraded to achieve this "cure" (79). Further, these lenses invalidate most color vision screening tests, particularly those based on carefully selected color confusion lines used to identify a color abnormal. Newer systems, such as ColorMax and ChromaGen lenses, have similar problems. Regrettably, no selective waveband filter (any colored filter) restores normal color vision to a color vision defective.

AIRCRAFT/ENGINEERING FACTORS

G Force (Gravity)

The visual system is profoundly affected in high-speed flight by acceleration (G forces), vibration, and a normal lag in human visual perception. On Earth, the human body is constantly affected by gravity, and this force is termed 1 G (sustained acceleration induced inertial forces). In flight, the speed, acceleration, and changes in direction can increase the amount and direction of this G force. These G effects are discussed in much more detail in Chapter 4 (Human Response to Acceleration); however, G forces have significant effects on the aviator's vision, and these effects will be discussed here. In flight, the aviator encounters linear acceleration, such as in catapult takeoff, aircraft

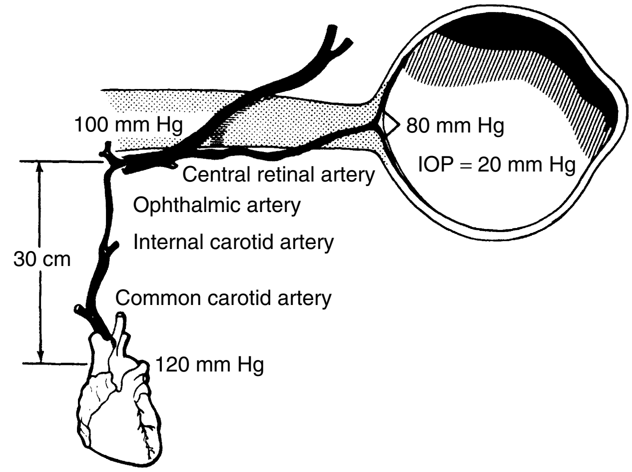


FIGURE 14-15 Normal arterial blood pressures from the heart to the eye.

carrier landings, ditching, and high-speed bailout. Radial acceleration is encountered in banks, turns, and pullouts from dives, loops, and rolls. Angular acceleration occurs in spins, in storms, and in tumbling following bailout from aircraft. It is the $+G_z$ acceleration that mainly concerns pilots, especially those in high-speed aircraft. When $+G_z$ are being pulled, the quantity of blood returning to the heart is diminished. The heart continues to beat, but diminution of the volume of systolic blood reduces the cardiac output, lowers the arterial tension, and causes a decrease in pressure. Figure 14-15 shows that with increasing G forces, a point will be reached when arterial pressure in the ophthalmic artery no longer exceeds intraocular pressure. It is at this point that visual function is definitely impaired and blackout ensues. However, sufficient perfusion pressure exists in the remainder of the central nervous system so that unconsciousness does not occur until the increasing G force further decreases the arterial pressure and the resulting pressure in the central nervous system is zero. On average, the pilot begins to lose peripheral vision at +3.5 to $+4.5\ G_z$. Blackout, or a complete loss of vision, occurs at +4 to $+5.5\ G_z$. Hearing, however, persists and orientation remains. From +4.5 to $+6\ G_z$ the pilot may lose consciousness. These are only average values, and they vary depending on the rapidity of onset of the G forces and the physical condition of the aviator. In the recent past, training, certain maneuvers, and protective clothing enabled the aviator to reach +8 to $+9\ G_z$ and maintain efficiency for longer periods. These factors entail improving one's physical condition, tensing of muscles, performing maneuvers, such as the M-1, and wearing improved anti-G suits. G-force protection could be further enhanced if reclining, tilting seats were available.

Negative G forces are not often encountered. If these forces were prolonged, however, they would result in congestion of the blood vessels of the upper part of the body, leading to a violent headache. Visually, a so-called red out may occur. The actual cause of this phenomenon is still unknown; it may be due to looking through a congested lower lid, which then acts as a filter. At high speeds, in order to maintain functional vision, one must maintain a radius of turn large enough so as not to cause excessive G loading. Table 14-2 shows the radii of high-speed aircraft turns that produce +6 G forces. For example, at a speed of 3,200 kph, pilots could not make a turn in a circle smaller than 27 km in diameter or they would black out unless performing the aforementioned protective maneuvers and were wearing good anti-G suits. Figure 14-16 shows the effects of acceleration and time on vision.

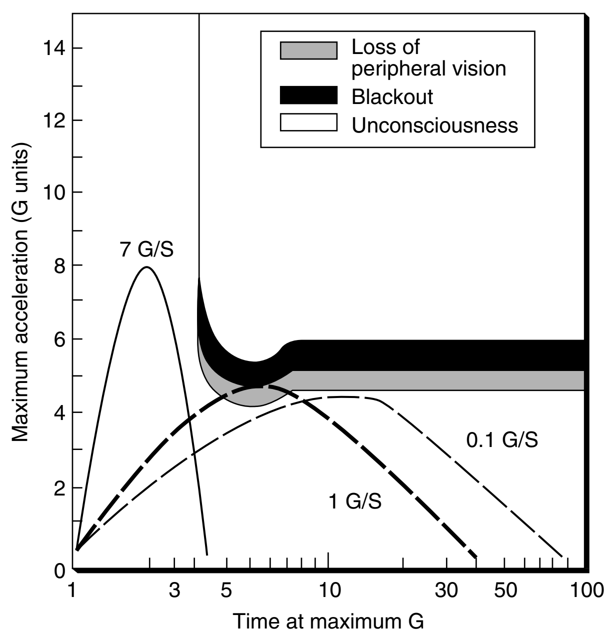
TABLE 14-2

Radii of High-Speed Aircraft Turns Producing +6 G Forces

Kilometers per Hour	*Meters*
400	209
1,200	1,882
1,600	3,395
3,200	13,597

Vibration

Vibration causes blurred vision and therefore reduces the visual efficiency of the aviator. Studies have shown that during vertical sinusoidal vibrations at frequencies above 15 Hz, visual acuity is degraded. Particularly degrading to



Acceleration and time at maximum G required to produce visual symptoms and unconsciousness. Curves showing different rates of G development are given to show the importance of this parameter for the occurrence of peripheral vision and blackout.

FIGURE 14-16 Visual effects produced by various $+G_z$ environments.

vision have been the frequency bands in the ranges of 25 to 40 and 60 to 90 Hz. When vibration cannot be avoided, its effect on visual performance can be reduced somewhat by the proper design of the visual instruments, displays, and printed materials, and an increase in their illumination and contrast.

Lag in Visual Perception

The length of time between an event and when the person sees the event depends on two factors: the length of time required for light to reach the eye and the conduction time in the visual pathways and brain tracts. Because of the speed of light, the interval between the event and the eye is an unimportant factor, but the lag in the visual mechanism is appreciable and, at supersonic speeds, turns out to be an important factor. This is demonstrated in Figure 14-17. Pilots flying at 1,000 kph see aircraft in their peripheral vision; they have traveled 28 m before the images are transmitted from the retina to the brain. They travel 300 m before they consciously recognize it. They travel more than 1 km before they have decided whether to climb, descend, or bank. They travel approximately 1.5 km before they can change their flight path. At 3,000 kph, speeds that can be attained in advanced fighter aircraft, all of these distances are tripled. The times noted here are probably absolute minimums and are not reducible by any mechanical or electronic ingenuity solely because they are unchanging characteristics of the human eye, mind, muscle, and nervous system. Conversely, the distance traveled at each interval will undoubtedly increase as the speed of new-generation aircraft increases. Further, one must also be aware that anything that would interfere with the pilot's vision, whether a structural component of the aircraft, the windscreen, his clothing, his spectacles, haze, or grayout induced by G forces, could greatly stretch out the time required to perceive and recognize an event. Pilots must not only identify the object as an aircraft, but also decide whether it is a friend or foe. The recognition time will then probably stretch out to perhaps 1.5 seconds, and duration time would probably be in the 4- to 8-second range rather than the 2 seconds indicated in the chart. A pilot may fly blind for thousands of feet while performing such simple operations as glancing at an instrument. At 1,000 kph, vision outside the aircraft is interrupted for approximately 1 km. At 3,000 kph, vision is interrupted for 2 km. In shifting sight from outside the aircraft to the instrument panel and back, the accommodation time (the time required for the eyes to focus on the instrument) becomes important. Accommodation and relaxation take up a total of 1 second, or 1 km at 3,000 kph (80). This is an important factor for the aging pilot who is losing the ability to accommodate. Recognition of the instruments consumes a good deal more than 0.8 second if they were poorly designed or poorly lit. Likewise, if the sky was bright and the panel dim, the pilot would first have to adapt to the dim light in the cockpit, then readapt to the brightness outside. One can do little to speed up these times. All of this shows that the modern pilot,

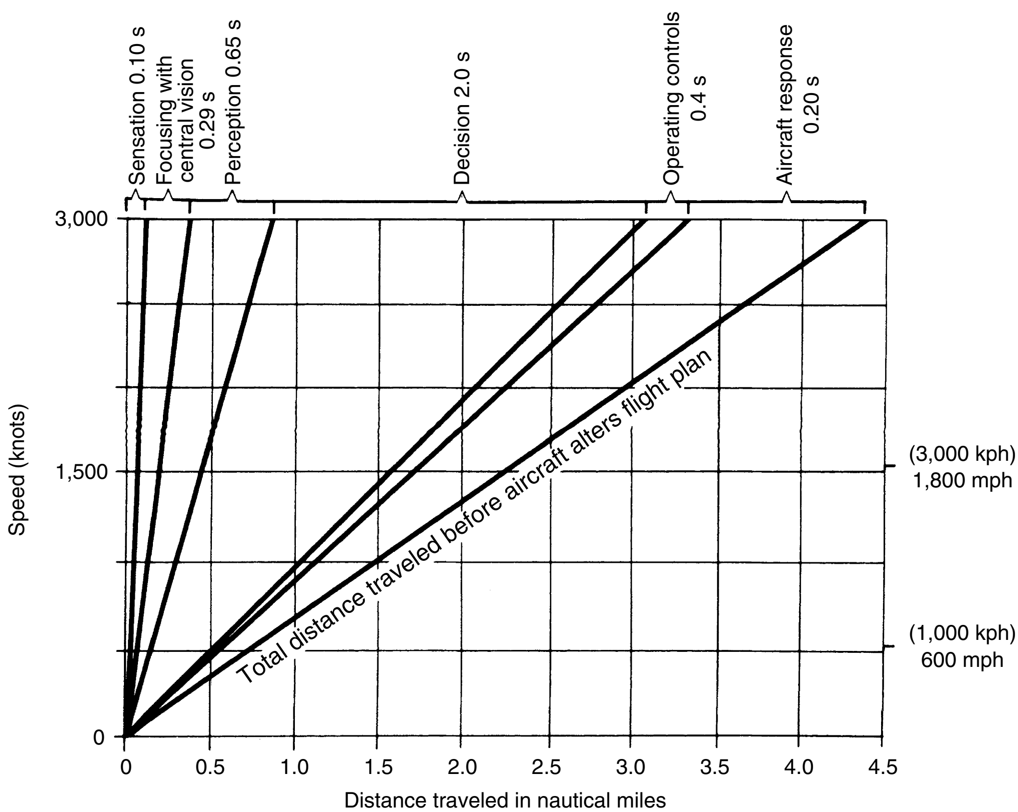


FIGURE 14-17 Distance traveled as a function of aircraft speed and visual processing.

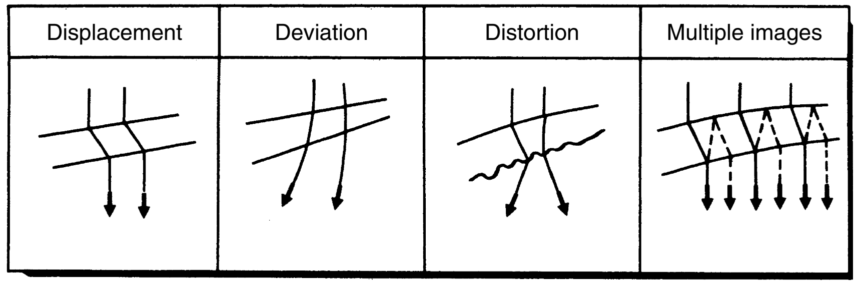


FIGURE 14-19 Windscreen optical effects.

especially in fighter aircraft, must be given the best design possible in illuminated cockpit instruments. Skimping in this area is unwise because a decrease in the pilot's visual efficiency does not allow for taking advantage of an otherwise superbly designed and powered aircraft.

Aircraft Windscreens

The pilot must, of necessity, look through several layers of transparent materials. One must look through the windscreen. One may also be using a visor, and, if one were ametropic, spectacles would have to be worn. Vision through these multiple transparencies may be distorted; therefore, it is imperative that the transparencies have a minimum amount of distortion and that the pilot should use as few as possible (Figure 14-18). Aircraft windscreens are shaped for aerodynamic reasons, and at times, these designs are not compatible with the requirements of good visibility. When only flat panels of glass were used in aircraft windscreens, the problems of distortion and multiple images were minimal. Newer aircraft demand compound shapes that can only be fabricated in plastic, and flying high-speed aircraft at low altitudes has introduced another peril: bird strikes. The combination of the aircraft and bird speeds can easily fracture any glass windscreen, necessitating multiple layers of new-generation plastic, such as polycarbonate, to withstand the impact created by bird strikes. This, however, has introduced another problem. Because the plastic windscreens are made of multiple layers of the material, a reflection of the image occurs at each layer, and these multiple images can become annoying and contribute to confusing visual effects for the pilot. Light rays striking the windscreen can be displaced, deviated, or distorted, or can cause multiple images, as shown in Figure 14-19. Optically, a flat, thin glass or plastic would be the most desirable from the visual standpoint. For the reasons mentioned previously, however, curved, thick, and laminated transparencies are a necessity in present-day aircraft. In the final design, a compromise has to be made between the aerodynamic, optical, and stress considerations (81).

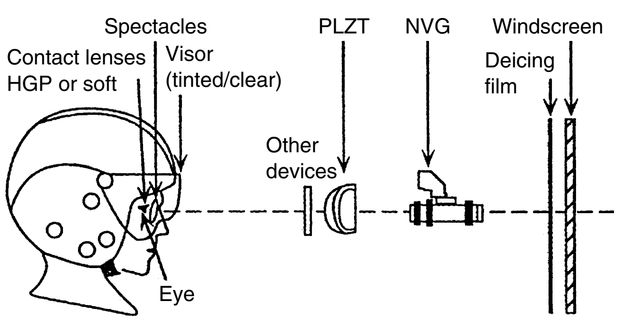


FIGURE 14-18 Different transparencies that may be interposed between a pilot and the world outside the aircraft. HGP, hard gas permeable; PLZT, lead lanthanum zirconate titanate; NVG, night vision goggles.

AVIATOR SELECTION—VISUAL STANDARDS

The visual selection of individuals for flying careers, the steps that need to be taken to maintain vision at peak efficiency, and the protection of the eyes from hazards that may affect the peak efficiency of the aviator's vision are discussed in this section. It cannot be denied that vision is the most important sense needed to fly an aircraft or spacecraft. In the early days of scarf, helmet, goggles, and open cockpits, good distance vision was by far most important. With the advent of closed cockpits and cluttered instrument panels, both distance and near vision became absolutely necessary. In modern closed aircraft, flying with spectacles is now acceptable when the refractive error is not too extreme. In military flying, especially in the new advanced fighters, however, spectacles are still a nuisance and, at times, are a definite disadvantage, because of the following:

1. They are uncomfortable on long missions.
2. High G forces may dislodge them.
3. A reduction of light transmission occurs through any transparency.
4. One more transparency is necessary to look through.
5. A limitation of the visual field occurs.
6. Spectacles have a tendency to fog.
7. They give annoying light reflections at night.
8. They are particularly difficult to integrate with other personal equipment.
9. High-refractive powers may cause aberrations and distortions of the image.
10. High-myopic corrections reduce the image size on the retina.

Selection of Candidates for Flying

The techniques used for the visual selection of candidates for flying should not be absolutely restrictive as to eliminate major segments of the population. Different visual demands are required for the aviator, depending on the mission and aircraft. Not all missions require maximum visual capabilities. The examination techniques should be able to select those who have an efficient and disease-free visual system.

Examination Techniques

History

One should attempt to elicit a complete ocular history from the patient. This would include any ocular disease, injury, medication, surgeries, loss of vision, double vision, and/or use of glasses or contact lenses. It would also be useful to get a family history of any ocular disorders, especially a history of glaucoma, night blindness, crossed eyes, cataracts, or color blindness.

Equipment for Ocular Examination

The following equipment will save time and make it easier to perform the ocular examination:

1. A flashlight and a second flashlight with a bare bulb that can be used as a point source of light
2. A distance target, which can be the flashlight with the point source of light
3. A near target, such as a tongue depressor with a small letter printed on it
4. Ophthalmoscope
5. Prisms to measure phorias and tropias if one were not using a vision screener
6. An occluder
7. A millimeter scale or a Prince rule
8. A loupe that magnifies approximately 2×

General Eye Examination

External Examination

The orbits are examined for any abnormality or asymmetry; exophthalmus or enophthalmus is noted. The eyes are then observed for any gross motility disorders or nystagmus. The presence of any tearing or discharge is noted. The lids are examined for symmetry and the presence of any ptosis. Lashes are observed and any inversion or eversion of the lids noted. Inflammation, cysts, or tumors of the lids and margins can quickly be discerned. The palpebral and bulbar conjunctivas can then be examined by everting the upper lid and depressing the lower lid. Here, one looks for hyperemia, injection, discharge, tumors, or pigmentation.

With the use of a flashlight, the pupils are examined. At this time, it should be noted whether any contact lenses are worn. Soft contact lenses are more difficult to detect, and it may be necessary to use the magnification of the loupe, or better yet a slit lamp, to see them. The pupils are examined for size, symmetry, position, and reaction (i.e., reaction to the light—direct, consensual, and accommodative). The Marcus Gunn pupillary sign is an extremely valuable indication of an optic nerve or retinal lesion. It is present when pupillary response to light is greater consensually than on direct stimulation, and it is elicited by the swinging light test.

The ocular examination is completed by observing the corneas, anterior chambers, irides, and as much of the lenses as possible with the flashlight and loupe. The corneas should be free of opacities and vascularization. With experience, the depth of the anterior chambers can be estimated, the irides are observed for any cysts, tumors, or unusual pigmentation and the lenses observed for opacities.

Corneal Topography

With the advent of refractive surgery, especially RK, PRK, and LASIK more advanced types of corneal examination and measurement have developed, allowing the examiner to know whether these procedures have been performed on the eye. Computer-assisted video keratography (corneal topography) has evolved as an instrument to accurately evaluate the status of the anterior corneal curvature (82). Early keratoconus can now be more readily diagnosed, and contact lens fitting is enhanced by having this more accurate corneal curvature data. Refractive surgical follow-up can also be more critically assessed.

Visual Acuity/Refractive Errors

At 6 m (20 ft), the entire letter on the 20/20 line subtends the visual angle of 5 minutes of arc. As shown in Figure 14-20, each component of the letter subtends 1 minute of arc, so that 20/20 indicates that at 6 m this individual can identify the component parts of the test letters. Vision should be tested in each eye separately, first without spectacles and then with spectacle correction. When they have below-normal visual acuity without correction and have no spectacles, patients may be tested with a pinhole of 2 to 2.5 mm in diameter. An improvement in visual acuity signifies that the subnormal vision is most likely due to a refractive error. If visual acuity was not to improve, most likely an opacity in the cornea or lens or a defect in the retina or optic nerve is present. If spectacles were used but did not improve the patient's visual acuity to 20/20, the pinhole test also can be used over the spectacles. An improvement in vision signifies that a change in the patient's prescription is indicated. Figure 14-21 shows the approximate visual acuity for spherical refractive errors up to +4 (hypermetropia) or −4 D (myopia).

Refractive errors are only rarely due to disease processes. They are mainly a mismatch between the diopteric power of the refractive system of the eye and the length of the globe.

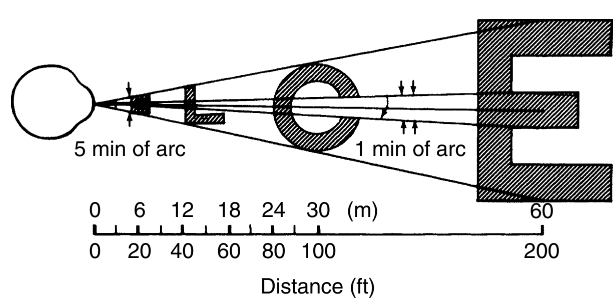


FIGURE 14-20 Geometry of visual acuity. (Adapted from Adler FH. *Physiology of the eye: clinical application. St. Louis*: C.V. Mosby Co., 1970.)

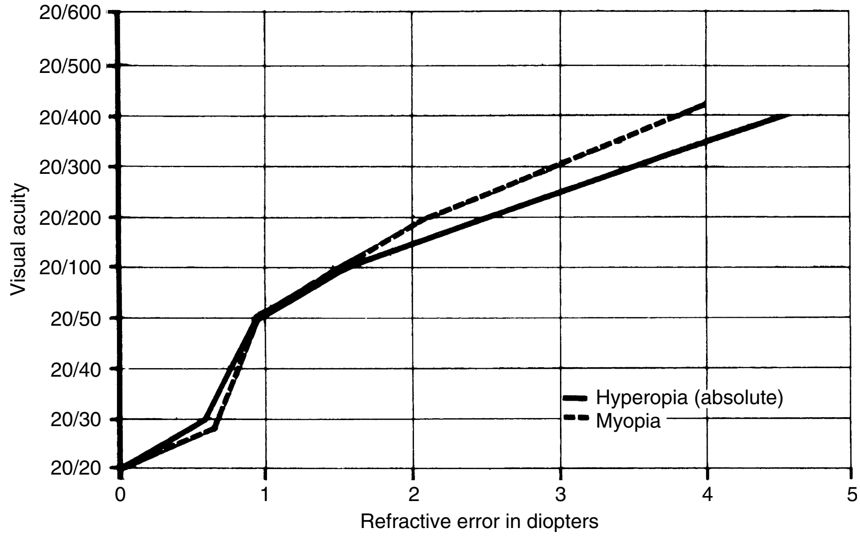


FIGURE 14-21 Visual acuity as a function of refractive error.

With a close match of these components, the individual is nearly or actually emmetropic. A mismatch can lead to hypermetropia (farsightedness) when the globe is too short for the refractive power, or the individual can be myopic (nearsighted) when the diopteric power of the refractive surfaces is too strong; therefore, the eye is relatively too long. The third and most common aberration is astigmatism. This is most often due to an asphericity of the cornea; that is, one meridian of the cornea has a higher dioptric power or is more curved than a second meridian located at 90 degrees from it. The rays of light passing through an astigmatic eye form a path known as *Sturm's conoid*. This form of astigmatism is known as *regular astigmatism* and can be corrected by cylindric and spherocylinder lenses. Occasionally, an eye is encountered that has irregular astigmatism; in this case, the maximum and minimum powers of astigmatism are not at 90 degrees, and this form of astigmatism can only be corrected by contact lenses. The hard contact lens can uniquely correct this deficiency because the tear film layer beneath the contact lens fills in the irregularities of the astigmatic cornea. However, a toric soft contact lens can also be used to correct the astigmatic error. If the candidate's vision were worse than 20/20, refraction should be required. A cycloplegic refraction is preferable because it totally relaxes the accommodation and therefore yields the true and total refractive error. This especially helps to delineate the refractive errors in hypermetropes because these young, farsighted individuals obscure the total amount of their error by exerting an accommodative effort, which corrects some part of the spherical error; however, accommodation does not help to correct a myopic error. In fact, accommodation increases myopia and makes the refractive error even worse. Astigmatic individuals may not be able to see clearly at either near or far distances. Only a cylinder or spherocylinder or contact lens correction can clear their vision. Accommodation may be of some help in mildly astigmatic individuals by shifting Sturm's conoid on the retina to the circle of least confusion. As is the case with the hypermetropic individual, however, this takes ciliary muscle effort, and symptoms of visual fatigue and blurred vision would ensue if the refractive errors were not corrected.

To see clearly at near distances, the dioptric power of the crystalline lens must be increased to an appropriate level for the distance of the object seen. After the age of 45, most individuals do not retain sufficient accommodation to see clearly at reading distances of 33 to 35 cm. This condition is known as *presbyopia* and must be corrected by plus lenses when one wishes to be able to read at near distances.

Distant visual acuity can be examined in a 6-m (20-ft) lane with an eye chart or a projector chart. A smaller room, such as a 3 to 4 m room, can be used with reverse charts and mirrors. Perhaps the best way for a flight surgeon or aeromedical examiner to check the visual acuity and other visual functions as well is by using a vision screener, such as the one shown in Figure 14-22. These instruments conveniently check a patient's distance and near visual acuities, phorias, and stereopsis. Without a screener, near vision can also be examined with a near vision test card held at 33 to 35 cm as per the instructions on the card. Each eye is tested separately.

Accommodation is tested in each eye separately using a Prince rule or its equivalent. One must be aware that

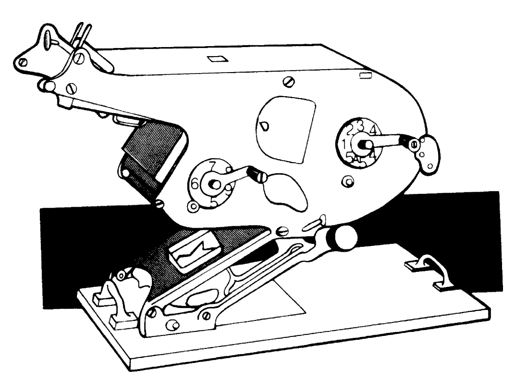


FIGURE 14-22 Vision screener used to assess visual function.

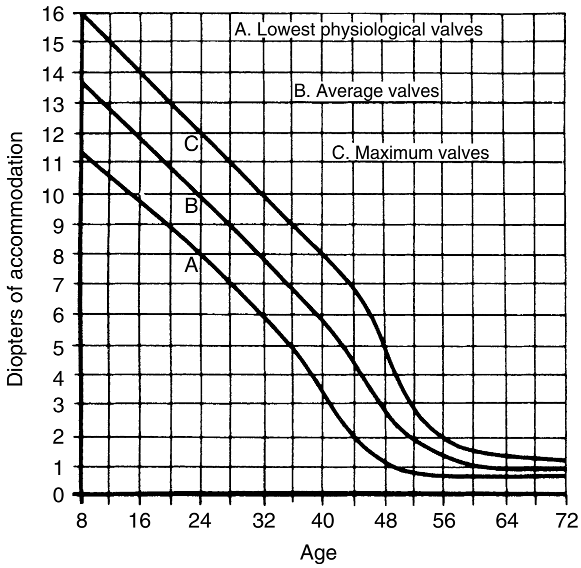


FIGURE 14-23 Accommodation-age curve.

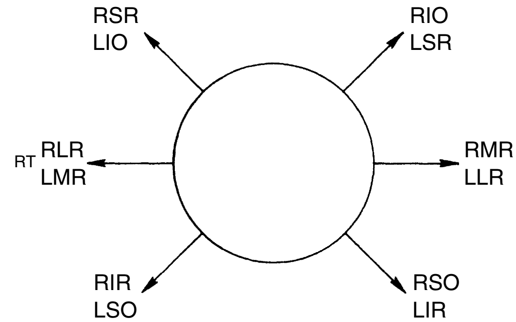


FIGURE 14-25 Yoke muscles. RSR, right superior rectus; LIO, left inferior oblique; RLR, right lateral rectus; LMR, left medial rectus; RIR, right inferior rectus; LSO, left superior oblique; RSO, right superior oblique; LIR, left inferior rectus; RMR, right medial rectus; LLR, left lateral rectus; RIO, right inferior oblique; LSR, left superior rectus.

when the patient has a refractive error, accommodation is tested through the spectacles. Should patients be presbyopic and wearing bifocals or trifocals, they must be tested only through the upper, or distance, part of the spectacles and not through the bifocal or trifocal. Allowing the patient to look through the bifocal portion alters the test and adds accommodative amplitude equal to the value of the strength of the bifocal. Figure 14-23 shows that accommodation normally decreases with age at an almost constant rate. It becomes manifest at approximately age 45 because most reading materials subtend a visual angle that is too small to see if held much beyond 0.3 m from the eye.

Motility

Normal ocular motility is expected in individuals who will be controlling aircraft. Diplopia or loss of stereopsis at a critical phase in flight could be devastating. The physician looks for straight eyes in the primary position of gaze and ensures that they remain so when taken into the six cardinal positions of gaze, as shown in Figure 14-24. As discussed earlier in this chapter, the six extraocular muscles rotate the eyes into infinite positions of gaze by the use of the yoke muscles operating under Hering's law of equal and simultaneous innervation to each yoke muscle. The yoke muscles and their actions are shown in Figure 14-25. A manifest deviation of the eyes is known as a *tropia* and can usually be observed by inspection and quantitated by the Hirschberg test, that is, observing the position of the corneal light reflex in the deviating versus the fixing eye, as shown in Figure 14-26. A phoria, conversely, is a latent deviation. It is only present when fusion (binocular viewing) is interrupted, such as by an occluder, a Maddox rod, or a red lens placed over one eye. Tropias are present in approximately 3% of the population, whereas phorias are present in approximately 100% of the population, meaning that, in essence, a phoria is normal unless it is extreme. It measures the resting state of the eyes. The eyes can be deviated inward, which is an esotropia or esophoria; deviated outward, which is an exotropia or exophoria; or deviated upward or downward, signifying hyper- or hypotropia or phoria.

An individual with a tropia (strabismus) may be seeing double, suppressing the vision in the deviated eye, or the eye may be amblyopic, with ensuing poor vision in that eye. Because almost all individuals have a phoria, it is not of too great a concern unless it is excessive. If the phoria were excessive, a large neuromuscular effort would be required to maintain fusion and, therefore, single binocular vision. Any added stress may cause a breakdown of fusion thereby leading to diplopia and loss of stereopsis. Hypoxia and fatigue are common stresses to the aviator, which can alter phorias; this is the principal reason for taking phoria measurements as part of the visual examination for flying. The easiest way for an aeromedical examiner to accurately measure phorias is by

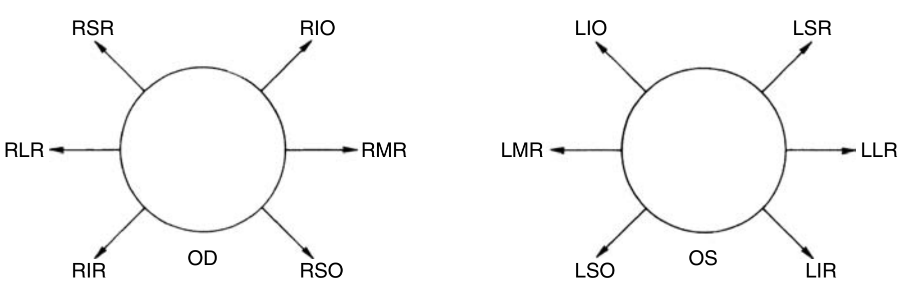


FIGURE 14-24 Muscle actions in the cardinal positions of gaze. RSR, right superior rectus; RLR, right lateral rectus; RIR, right inferior rectus; OD, right eye; RSO, right superior oblique; RMR, right medial rectus; RIO, right inferior oblique; LIO, left inferior oblique; LMR, left medial rectus; LSO, left superior oblique; OS, left eye; LIR, left inferior rectus; LLR, left lateral rectus; LSR, left superior rectus.

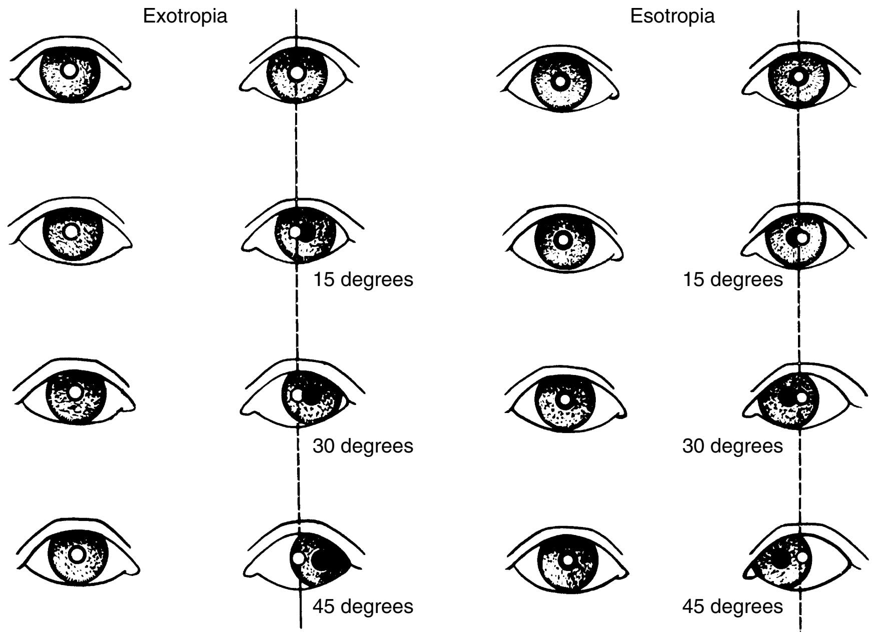


FIGURE 14-26 Hirschberg reflex test used to detect tropias.

use of a vision screener. Ophthalmologists and optometrists mainly use a Maddox rod, occluder, and prisms in the eye lane to detect and measure phorias. As has already been mentioned, the Hirschberg (inspection) test delineates a large-angle tropia. Small-angle tropias can only be detected by the cover test.

The near point of convergence is also important in this examination because it too is influenced by hypoxia and fatigue. The near point has a tendency to recede under these conditions. Normally, the near point of convergence is 100 to 120 mm from the eye, but in military aviators, the near point of convergence is expected to be 70 mm or less. The Prince rule can be used to do this test. A small, dim light or a small test target is brought forward along the rule until the patient breaks fusion and sees double. Simultaneously, the examiner notes that one of the eyes deviates out. A measurement at that point is the near point of convergence and should be within acceptable limits.

When the examiner notes nystagmus, whether it is pendular or rotary, when occluding an eye, the patient should be sent to an ophthalmologist for a complete evaluation.

Color Vision

A variety of tests is available to test for color vision defects. They have been discussed in the section **Color Vision**.

Stereopsis/Depth Perception

Tests of binocular vision given to aviators are usually referred to as *depth perception tests*. In reality, they are tests of stereopsis, one component in the perception of depth. Visual screeners, such as the Bausch and Lomb, Titmus, Keystone, or OPTEC, with excellent test slides quantify stereopsis down to as fine as 15 seconds of arc. Military flyers are expected to have stereopsis of at least 25 seconds of arc disparity. These tests, done in visual screeners, are at optical infinity; therefore, they are distance tests. Near tests of stereopsis are also available, such as the Verhoeff, with its three bars of varying width. This test is administered at 1 m without any special optical devices. The patient should be wearing spectacles, when needed, to correct for distance, and the patient must have no failures in the eight presentations to pass the Verhoeff depth perception test. This equals approximately 32 seconds of arc disparity. Another commonly used near-stereoscopic test is the Wirt. This test necessitates using polarizing glasses but has the disadvantage of only going to 40 seconds of arc disparity. Normal room illumination is used for all three stereo tests.

Field of Vision

Aeromedical examiners need only do confrontation fields, which compare the monocular field of the examiner and the patient. Any aberration in this field examination or history of neurologic disease or increase in intraocular pressure necessitates that a more precise perimetric study be done on a tangent screen or perimeter. Perimeters, such as the Goldmann hemispheric, have been the standard since the late 1950s. However, over the recent past, automated static threshold perimetry has become the new standard for evaluating the visual field, especially in patients with glaucoma. The Humphrey and Octopus models are the most popular. The extent of normal visual fields is shown in Figure 14-27.

Night Vision

Night vision is not routinely tested unless indicated by history. If a history of difficulty in seeing at night were elicited, dark adaptometry would be indicated. This test must be accomplished by referring the patient to a center that has an adaptometer.

Intraocular Pressures

Glaucoma is a disease of maturity. Most of the glaucoma seen in aircrew members is of the open-angle variety, which

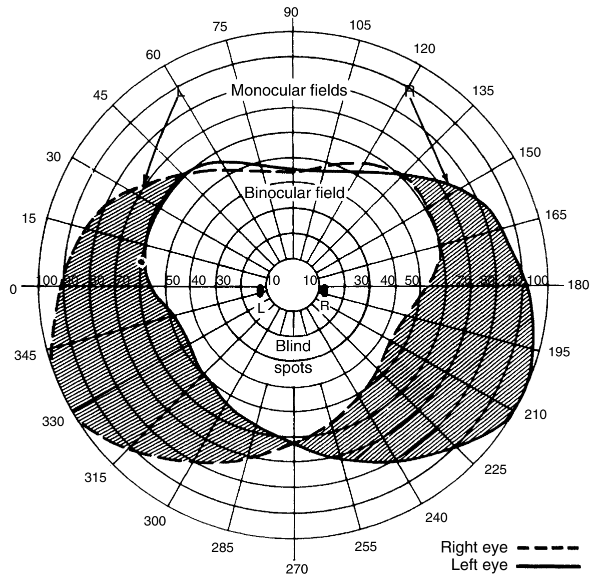


FIGURE 14-27 Normal visual fields.

is not commonly found in individuals younger than 40. The intraocular pressure measurements should be done in individuals aged 30 or older. If, however, a family history of glaucoma were to exist, intraocular pressure measurements should be done at any age. Yet, recently more patients with "pigmentary glaucoma" are being diagnosed. This is an open-angle type of glaucoma with pigment derived from the iris, causing a blockage of the trabecular meshwork (83). These individuals, who are usually mildly myopic, are first noted to have pigmentary dispersion syndrome, with a worsening of this condition to pigmentary glaucoma. The USAF now screens aviators for an increase in intraocular pressure beginning at age 29 and at each complete physical thereafter. Schiøtz (indentation) tonometry is most readily available for the aeromedical examiner. Applanation tonometry is an excellent technique; however, this takes more practice and requires the availability of an expensive slit lamp or handheld Tono-Pen tonometer. In any case, the results are comparable regardless of which instrument is used. Space-age technology has brought us the air or puff tonometer. It also gives reliable results in experienced hands. Any intraocular pressures consistently greater than 21 mm Hg should be referred for a full glaucoma workup. Most of these individuals will be found to have only intraocular hypertension; that is, they will show an increase in intraocular pressure without any field loss or disc cupping. This condition generally requires no treatment; however, these individuals must be followed up carefully at regular intervals, such as every 3 to 6 months, with intraocular pressure measurements, ophthalmoscopy, and visual field examinations. If their conditions were to deteriorate, as indicated by scotomas in the visual field or abnormal cup-to-disc ratios, treatment would be indicated and consultation should be sought from an ophthalmologist immediately. New objective techniques are in development that will analyze the optic nerve and nerve fiber layer for evidence of glaucomatous damage. Presently these consist of stereo-video cameras, confocal laser systems, scanning laser ophthalmoscopes, and optical coherence tomography (84).

Internal Ocular Examination

The final part of the examination for flying is an examination of the clear media and fundus of the eye. To get a good look at the fundus, the pupils should be dilated. In light-colored irides, two drops of 2.5% phenylephrine will suffice to dilate the pupil without altering the accommodation. With a darker-colored iris, a short-acting cycloplegic agent will probably have to be added to dilate the pupil sufficiently to view the fundus. One drop of 1% cyclopentolate or 1% tropicamide along with one drop of 2.5% phenylephrine will dilate the pupil for several hours. The examiner views the patient's right fundus with the right eye, and then switches the direct ophthalmoscope to the left eye to view the left fundus. A +6 or +8 D lens is rotated in the ophthalmoscope, and the red reflex is visualized at approximately 15 cm from the eye and examined for opacities, streaks, or any other alterations. If any of these conditions were noted, the patient should be referred for a consultation.

Normal fundus details are shown in Figure 14-28. Individuals with any fundus abnormalities should be referred to an ophthalmologist for diagnosis and possible treatment.

Maintenance of Vision

Individuals preparing for a lifelong career in aviation should have a thorough ophthalmologic examination. For a civilian or military flying career, long-term prediction of the health of the visual system is extremely important because it is expected that the aviator will serve for at least 20 years. Examiners should strive to select individuals with excellent visual capabilities who are up to the visual demands of the duties to be performed. The selection of individuals with disease-free visual systems will go a long way toward assuring a 20+ year flying career. Periodic reexaminations will aid in maintaining a disease-free ocular system. Proper nutrition is vital to the maintenance of the visual system. Vitamin A is necessary for night vision and to aid in the production of visual pigments, whereas the water-soluble B vitamins protect against nutritional amblyopia. Protection from physical forces in daily activities, sports, and in the aircraft is important. Protection from excess electromagnetic

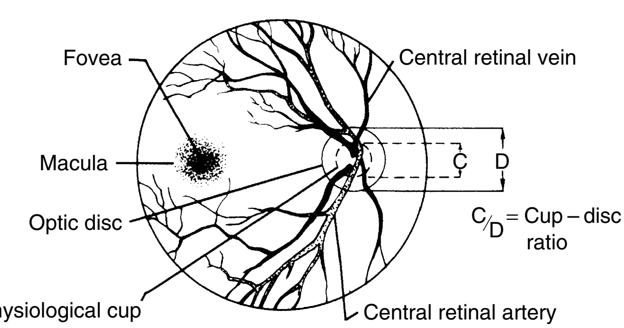


FIGURE 14-28 Normal fundus details.

energy is also a necessity. This energy can be an occupational hazard encountered in aviation. If ocular disease or injury were found, proper, timely, and correct treatment would speed recovery. This treatment should be followed by a reevaluation to consider the degree of impairment, if any, and its possible effects on the aviator's flying efficiency. Finally, the aeromedical examiner or flight surgeon should educate all aircrew in the proper use and care of their eyes and vision.

Many drugs are used to diagnose and treat ocular conditions. Most of these drugs should be left to the use of the ophthalmologist; however, the aeromedical examiner should have a basic knowledge of the action of certain commonly used drugs on the eye. The eye is an excellent field to observe the pharmacodynamics of the autonomic nervous system. Both the sympathetic and parasympathetic parts of the autonomic nervous system innervate the pupil and ciliary body. The dilator muscle of the pupil is innervated by the sympathetic nervous system, and the sphincter is innervated by the parasympathetic nervous system. The ciliary muscle involved in accommodation is innervated by the parasympathetic nervous system. Some common ophthalmic drugs and their actions are summarized in Table 14-3.

The aeromedical examiner should consult an ophthalmologist when atropine or steroid preparations are to be prescribed. Finally, one should never prescribe ocular anesthetic agents for use by the patient.

CONDITIONS AFFECTING THE AVIATOR'S VISION

Once selected with a disease-free visual system, the aviator usually remains so for several decades except for minor refractive changes and the universal onset of presbyopia in the fifth decade of life. Young flyers, especially those who do not use spectacles, may become victims of ocular trauma. Ocular trauma can be devastating to a flying career. Aeromedical examiners should warn their patients to use protective goggles or impact-resistant spectacles for all sports in which a high-speed missile may be involved, such as handball, tennis, squash, and hockey. Injuries to the eye should be referred at once for definitive diagnosis and treatment. In the older aviators, glaucoma or ocular hypertension is often encountered. With the latest medical philosophy on when treatment for glaucoma should be instituted and with new medications that do not secondarily affect vision, one need not fear the effects of glaucoma on a flyer's career. Observation and the treatment regimen pioneered at the USAF School of Aerospace Medicine (USAFSAM) have kept 95% of these Air Force patients on flying status for a full career (85). Those individuals with intraocular hypertension (intraocular pressure >21 mm Hg but <30 mm Hg, without field defects) are observed at regular intervals without treatment. Those individuals

TABLE 14-3

Common Ophthalmic Drugs

Dilate pupil	
Adrenergic (Sympathomimetic; Dilating, Direct-Acting)	*Anticholinergic (Parasympatholytic; Competitive Antagonists to Acetylcholine)*
Epinephrine (α and β)	Atropine
Norepinephrine (α)	Scopolamine
Phenylephrine (α)	Homatropine
Isoproterenol (α)	Cyclopentolate
Timolol (β-blocking)	Tropicamide
Constrict pupil—cholinergic (parasympathomimetic)	
Direct-Acting	*Indirect-Acting (Anticholinesterase)*
Pilocarpine	Edrophonium
Carbachol	Isofluorophosphate (DFP)
Methacholine	Echothiophate

Drug	*Concentration (%)*	*Begin Effect*	*Duration*
Pilocarpine	0.5–6	15 min	4–6 hr
Tetracaine (Pontocaine)	0.25–0.5	1 min	15 min
Proparacaine (Ophthaine)	0.5	30 s	10 min
Lidocaine (Xylocaine)	1, 2	5 min	3–4 hr
Phenylephrine (Neo-Synephrine)	2.5, 10	10 min	2 hr
Atropine	0.5–2	2 hr	7–14 d
Homatropine	2–5	30 min	6 hr
Cyclopentolate (Cyclogyl)	0.5, 1, 2	15–30 min	24 hr
Tropicamide (Mydriacyl)	0.5, 1	15–20 min	2–3 hr

with glaucoma (>30 mm Hg or with visual field or optic disc changes at any pressure) are treated with either levo-epinephrine, β-blocker, or prostaglandin analog eye drops with remarkable success without creating secondary visual aberrations. Further, a number of new ocular drugs such as topical carbonic anhydrase inhibitors, α-adrenergic agonists, and prostaglandin analogs are now available for treatment of glaucoma and ocular hypertension (86). The laser has also been used to treat glaucomatous conditions. For instance, trabeculoplasty is now often used for open-angle glaucoma treatment. Microscopic laser burns are placed in the trabecular meshwork. This enhances the outflow of aqueous and may eliminate the need for ocular medications. In the more rare, narrow-angle glaucoma, the laser can be used to create an iridotomy. Previously, this necessitated surgical iridectomy. Both of these procedures are used in aviators, allowing them to return to full flying duties.

Retinal disorders are also seen in the younger patients. Central serous retinopathy, an edema of the macula of unknown origin, plays havoc with a pilot's stereopsis/depth perception. Fortunately, 97% of these afflicted individuals recovered and were returned to full flight status as noted in a review of USAF aviators with this condition (87). Older flyers may develop macular degeneration that may eventually end their flying careers because presently no effective treatment exists for this condition.

A small number of flyers may develop keratoconus or irregular astigmatism, but many of these individuals can be returned to full flight status by the proper fitting of toric or hard-contact lenses. A USAF study showed that 82% of USAF aviators with a diagnosis of keratoconus were returned to full flight status (88).

A fair number of individuals have migraine, but only a few flyers complain of it to the aeromedical examiner. The most significant aspect of this condition for flying personnel is developing a central scotoma during an attack or becoming incapacitated by the headache that may follow.

Cataracts are commonly seen in the older flying population or as a result of ocular trauma at any age. If the opacity is dense enough, it could affect vision and, therefore, a flyer's career. Modern surgical procedures and postoperative optical correction either by an intraocular lens placed into the eye at surgery or by a contact lens fitted after surgery may allow many individuals to pass the visual examination and return to flying. Recent data shows that these procedures are quite successful, even in military aviators. In 80 eyes with intraocular lenses, 96% attained 20/20 visual acuity and 86% of those affected were returned to full flight status, 3 being grounded for nonophthalmologic disease, and 3 for ocular complications. The longest follow-up in these patients has been 20 years (89).

Correction of Refractive Errors

Standard Techniques

Refraction is a procedure used to determine the lens power needed to correct a patient to emmetropia. The refractive error can be estimated by retinoscopy, which is usually done following the use of cycloplegic eye drops. A manifest or subjective refraction is done with lenses, crossed cylinders, or astigmatic dials, and a third and common way of calculating the refractive error is with a lensometer, which measures the patient's present spectacle correction. If spectacles were to correct the patient's vision to 20/20, nothing further would need to be done concerning the refraction. The aviator's distance refraction changes little during the ages of 20 to 40. After the age of 40, although the error for distance may remain static, a correction for early presbyopia is often necessary. Spherical plus lenses correct the deficient accommodation. Once presbyopia has commenced, the patient needs to be reexamined every 2 years to maintain clear, comfortable near vision. A half-eye spectacle will suffice for the patient with no error in distance vision, but bifocals will be needed to correct the error in those who also require a correction for distance. Trifocals and newer progressive lenses may be helpful to the older pilot needing correction for both near (reading) and intermediate (panel) distances.

The use of contact lenses to correct refractive errors began more than 50 years ago. They have found acceptance in civilian aviation and since 1989 have been used in military aviation.

After a formidable research effort, the USAF now allows its aviators to use soft contact lenses in place of spectacles. A limited number of tested soft contact lenses are approved for use. Flyers with astigmatism over 0.75 D are fitted with toric soft lenses. The major problem encountered has been the dry cockpit environment. To date, the USAF Soft Contact Lens Program has been a success (90). Hard gas permeable (HGP) lenses are made of silicone-acrylate, and soft contact lenses of hydroxyethylmethacrylate (HEMA) and silicone plastics. The hard lenses are used in a limited manner to correct visual defects, such as irregular astigmatism, keratoconus, and aphakia. The soft contact lens is more comfortable to wear, less time is needed for adaptation, and the soft lens rarely alters the corneal curvature. Soft lenses, however, do have a significant drawback for aviators in that they cannot correct astigmatism of more than 0.75 D. In certain individuals, hard lenses may temporarily or permanently mold the cornea to a different refractive status or curvature. This could fortuitously improve the vision or it could lead to corneal warping and degrade visual acuity.

Newer Techniques for Refractive Error Correction

Orthokeratology

More than three decades ago, some practitioners began using contact lenses purposely fitted flat to reduce corneal contour and improve uncorrected vision, a procedure called *orthokeratology* (to straighten the cornea). While this technique can alter the corneal curvature, it is highly unpredictable and not permanent (91). It requires the use of so-called retainer contact lenses to maintain the effect; however, most corneas revert to their original curvatures and refractive errors in several weeks once these lenses are discontinued. Regrettably, this procedure can cause "with-the-rule" astigmatism that mimics keratoconus or even a decrease in vision from corneal scarring.

Refractive Surgery

CRS procedures have now been developed to more permanently alter the refractive status of the eye. Although, most of these procedures were developed to correct myopia, CRS techniques are now also available to correct hyperopia and astigmatism. One of the earliest myopic procedures was a rediscovered technique from the 1950s called *radial keratotomy* (RK). RK involves making four or more radial incisions in the corneal stroma down to the depth of Descemet's membrane, reaching radially to the limbus, but sparing the central 3 to 4 mm optical zone over the pupil. These weakening incisions flatten the central cornea, thereby decreasing the amount of overall myopia. As with orthokeratology, corneal response to RK incisions is variable and unpredictable; but much more permanent (92). Although rarely performed now, pilot aspirants in the past willingly underwent RK hoping to qualify for aviation careers. Presently, most military services do not allow RK because of reduced corneal integrity, long-term instability (progressive hyperopic shift), daily fluctuations in vision, glare, altitude effects and because even longer-term consequences of RK remain unknown (93,94). Fortunately, RK has been almost completely replaced by newer and more effective CRS procedures in most countries.

More recently, newer forms of CRS have emerged using lasers, such as the 193 nm ultraviolet excimer laser, to ablate and flatten the central cornea. Myopic procedures using this laser can be categorized into surface ablations, most notably PRK and its variants [laser epithelial keratomileusis (LASEK) and epi-LASIK], or deeper ablations performed beneath a hinged corneal flap, known as *laser in-situ keratomileusis* (LASIK). LASIK flaps can be created with a mechanical microtome, or more recently, using a femtosecond infrared laser (IntraLase) (95,96).

In general, corneal haze following CRS appears more of a problem with PRK than LASIK. However, the LASIK corneal flap never heals completely and remains chronically unstable, which may be problematic in certain vocations and occupations. For example, incidental levels of corneal trauma have been shown to dislocate LASIK flaps up to 6 years after the procedure, so far (97). In addition, altitude, windblast, water-blast, and G effects remain significant potential threats to LASIK eyes long-term. Adequate aeromedical studies to investigate these LASIK concerns have not yet been done. Despite this, LASIK has become more popular than PRK because of faster results, less corneal haze, and reduced ocular pain in the immediate postoperative period. However, this gap is narrowing because newer analgesics have made PRK virtually pain-free and advanced wave-front analysis (custom-CRS) appears more effective with surface ablations, making custom-PRK a potentially more suitable procedure for the aviator (98).

Both PRK and LASIK are mainly used for the correction of myopia up to −8.00 D, but more recently also for treating hyperopia and astigmatism. Complications, however, increase as the amount of myopia increases. Other hyperopic CRS techniques, for example laser thermal keratoplasty, use IR lasers to induce central corneal steepening from circumferential thermal burns. Nonlaser CRS techniques, such as intrastromal corneal implants (Intacs) and implantable intraocular contact lenses (ICLs) exist, but each of these has more limited application because aeromedical uncertainties will limit their indications and appeal (99–101).

The literature reports that 89% to 98% of low myopes obtain 20/40, and 65% to 80%, 20/20 or better visual acuity, following CRS (102). Accuracy to within ±1.00 D varies between 75% and 95%, depending on amount of preoperative myopia (103). Questions remain, however, whether the postoperative goal of 20/20 is adequate, given preoperative best-corrected means of 20/13 in trained and applicant aircrew populations around the world (104–106). Postoperative corneal haze and induced higher-order wave aberrations from CRS can affect the overall quality of vision and cause haloes and glare, especially under low light when the pupil dilates. Contrast sensitivity function, the ability to see under less-than-ideal conditions, has also been shown to be decreased even beyond 12 months following both procedures. Predictability for aviation remains a problem. If one were corrected to within the "1.00 diopter" accuracy, the 20/20 uncorrected visual acuity desired for a pilot would not be met. Finally, the possibility of regression and the risks of retinal detachment long-term remain after CRS. Regardless, PRK and LASIK have been approved by the U.S. Federal Drug Administration (FDA), FAA, and are now allowed by the U.S. military for most career fields to include flying. Continued studies, however, are needed to determine the full operational impact of modern CRS on aviators, particularly for military aviation.

PROTECTION OF VISION

Ocular Protective Materials

Since June 1972, all spectacle lenses used in the United States have had to be impact resistant by an FDA ruling. Impact resistant does not mean that they are unbreakable, just that a glass lens must withstand a 5/8-in. diameter steel ball dropped on it from a 50-in. height. Glass lenses are hardened to withstand the drop-ball test by heat or chemical tempering.

A plastic, allyldiglycol carbonate (CR-39) lens may also be used in place of glass. A transparent plastic polycarbonate (Lexan) is being used in helmet-mounted visors and as a cockpit transparency that is strong enough to withstand bird strikes. Bird strikes are hazardous to low-flying, high-speed aircraft. The combination of a multilayered polycarbonate windshield and a visor of similar material for the aviator's helmet have markedly improved the protection against this lethal hazard. A dual-visor system, one clear and one tinted, allows for maximum protection under all flight conditions. Polycarbonate lenses are now available in lenses to correct refractive errors. For sports and occupational activities, polycarbonate can be used as a protective goggle over ordinary spectacles, or can be placed directly into spectacle frames, thereby correcting the visual acuity and protecting the eyes. This material also has a secondary benefit in that it protects against ultraviolet light. It begins to transmit at 385 nm, blocking all shorter wavelengths. However, it is susceptible to scratching and costs more (107).

Filters and Sunglasses

The extent and effects of electromagnetic energy (light) on the eye have been previously discussed. As noted, light intensities in the aviation environment can be up to 30% higher than on earth. Abiotic ultraviolet radiation (200 to 295 nm) is filtered by the atmosphere but does begin to become significant at high altitudes. Ultraviolet radiation 300 to 400 nm, which is abundant on Earth, is now reputed to have some damaging effect on the human lens following long-term, chronic exposure and may be linked to macular degeneration. IR radiation above 760 nm is a contributor to solar and nuclear retinal burns. Sunlight falling on the earth is composed of 58% IR energy (760–2,100 nm), 40% visible light (400–760 nm), and only 2% ultraviolet radiation (295–400 nm). At high altitude, ultraviolet radiation may be as high 4% to 6% and makes up 8% to 10% of the solar energy spectrum in space. Sunglasses can protect the aviator from excessive and harmful electromagnetic energy.

The ideal sunglasses for the aviator should do the following:

1. Correct refractive errors and presbyopia
2. Protect against physical energy (wind or foreign objects)
3. Reduce overall light intensity
4. Transmit all visible energy but attenuate ultraviolet and IR radiation
5. Not distort colors
6. Not interfere with stereopsis (depth perception)
7. Be compatible with headgear and flying equipment
8. Be rugged, inexpensive, and need minimal care

Five types of sunglasses are now in common use: colored filters, neutral filters, reflecting filters, polarizing filters, and photochromic filters. They all allow only a certain percentage of the total amount of incident light to get through to the eye but produce this effect in different ways. The colored, neutral, polarizing, and photochromic filters do this by absorbing some of the light and allowing the rest to pass. Spectral filtering is achieved in glass lenses by adding specific chemicals to the melt, producing a through-and-through tint. The anterior surface of the glass lens also may only be tinted, but this method is subject to scratching. Plastic lenses are usually dipped into dyes to produce their filtering effect.

Colored filters have the disadvantage of altering the color of viewed objects and may reduce color discrimination of color vision–deficient persons.

Neutral filters adequately reduce the amount of light. Mainly, they do not distort colors and most will adequately eliminate excessive IR and ultraviolet radiation.

Reflecting filters can be coated uniformly. They eliminate the ultraviolet and IR energy; however, this type of coating scratches and peels easily and gives a greenish tint to objects.

Polarizing filters reduce glare off water or highways. For the aviator, they can cause a problem, such as blind spots in windshields and canopies, due to stress polarization induced by the canopy, matching that in the spectacles. Plastic polarized filters scratch easily and, when laminated in glass, are expensive and heavy.

Photochromic filters (variable light transmission) are photodynamic lenses that vary in intensity in response to the ultraviolet content of the incident light. Some flyers may find the darkest density sufficient; however, for aviation use, the range of transmission variation is not adequate. The darker lenses remain too dark in the "open" state, and the lighter lenses are not dark enough at their maximum density (108). Density and cycling time can be reduced, particularly in hot and low-ultraviolet environments, such as inside automobiles or cockpits, where ambient light is altered traversing another transparency. This is shown in Figure 14-29, which also compares these lenses with other filters.

Selection of Sunglasses for the Aviator

The lens material should be CR-39 or polycarbonate plastic or impact-resistant glass. After much experimentation, a 15% neutral density–transmitting lens probably represents the best all-around compromise for aviation. Some individuals prefer a 25% transmitting lens for daily use (e.g., driving or sports) but switch to the 15% transmitting lens for aviation use. The lens should have a fairly flat transmission curve in the visible energy range to preserve normal color vision but attenuate the ultraviolet and IR radiation. An ideal transmission curve is shown in Figure 14-30.

The difference in overall transmission between the two spectacle lenses should not be greater than 10%; otherwise, this disparity will induce the Pulfrich effect as that may

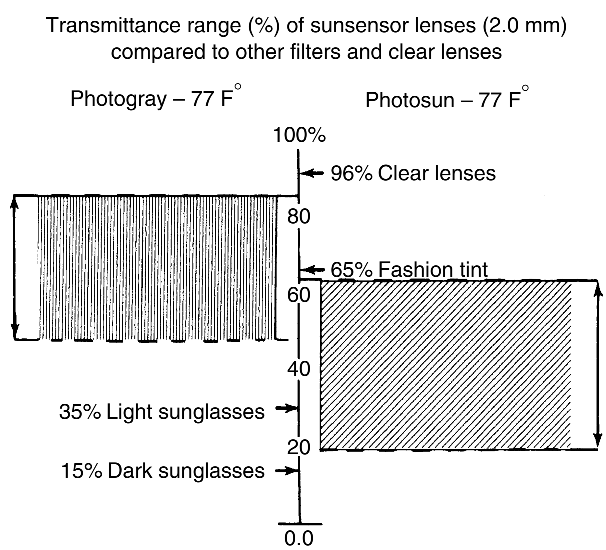


FIGURE 14-29 Effectiveness of various tints of lenses in reducing light transmission.

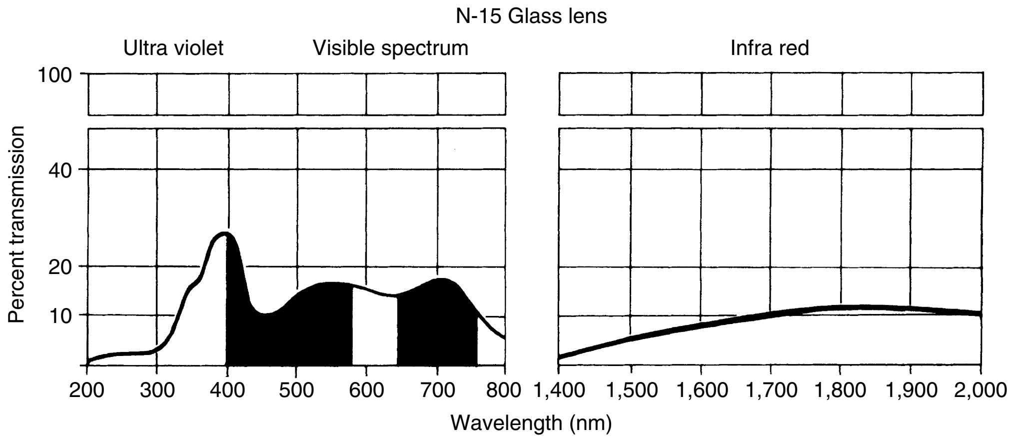


FIGURE 14-30 Idle transmission curve for sunglasses for the aviator.

degrade stereoscopic vision and depth perception. When sufficient overall light intensity is present, such as in daylight, visual acuity through 15% neutral density, transmitting lenses will be as good as in the eye lane without filters. Under low-light levels, such as at dawn or evening and on dark cloudy days, sunglasses reduce both contrast sensitivity and central visual acuity and, therefore, should be removed. Much has been said concerning certain selective waveband filters known as *blue blockers* that cut off all ultraviolet and blue portion of the spectrum. Cutting out any of the colors in the spectrum is not desirable in aviation. The aviator's "neutral density" sunglass lenses allow all colors through and effectively reduce ultraviolet light as well.

Under extraordinary conditions, electromagnetic energy may reach such a magnitude that ordinary protective devices will not be adequate. Such tremendous amounts of energy can be released during a nuclear detonation or packaged in a laser beam making protection of the eye against these energy sources is a must; otherwise, permanent injury to the eye will ensue (109).

Nuclear Flash Protection

In spite of the fact that the nuclear weapons threat has been dramatically reduced, it still remains; therefore, the material to follow has more than an historical interest.

The eye is more susceptible to injury from nuclear explosions at far greater distances than any other organ or tissue of the body. When a pupil of a given size is exposed to a nuclear detonation at a given distance, it will result in a certain amount of energy being distributed over the image on the retina. When one doubles the distance from the detonation, the amount of energy passing through the same size pupil will be only one fourth as great. The image area on the retina, however, will be only one fourth as large; therefore, the energy per unit area will remain constant irrespective of the distance from the detonation except for the attenuation due to the atmosphere and ocular media. The potential danger of flashblindness and chorioretinal burns resulting from viewing nuclear fireballs remains a threat to aircrew members.

During daylight, with high-ambient illumination and through a small pupillary diameter, the retinal burn and flashblindness problems are greatly diminished. At night, with a large pupil, protection is a must. Many different ideas for eye protection have been advocated. Fixed-density filters, on either the pilot or the windscreen, electromechanical and electro-optical goggles, explosive lens filters, and phototropic devices have been developed. The sum total of all this work is that a 2% transmission-fixed filter, gold-plated visor gives adequate protection against retinal burns and reduces flashblindness to manageable proportions during daylight. This filter, however, cannot be used at night. Another aid, a readily available countermeasure to flashblindness, day or night, is the ability to raise instrument panel illumination by auxiliary panel lighting to 125 ft-c. This increased illumination significantly reduces visual recovery time. The ideal "omni" protector against nuclear flash is still being sought. The most recently developed material for protecting against nuclear flash is a transparent ferroelectroceramic material (lead lanthanum zirconate titanate, PLZT) placed between crossed polarizers, as shown in Figure 14-31, reacts to the light energy of detonation within 50 to 100

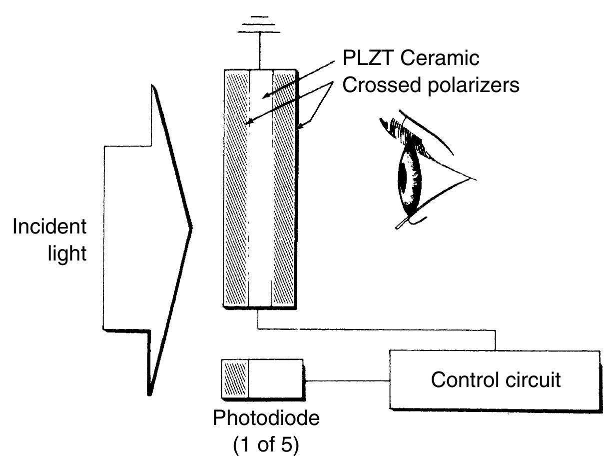


FIGURE 14-31 Flash-blindness-protective goggles. PLZT, lead lanthanum zirconate titanate.

milliseconds, reaching an optical density of 3. Its largest drawback is that in its open state, it transmits only 20% of the light. It may also be of interest that the 2%-transmitting gold-plated visor, developed at the USAFSAM for protection of aircrew against the flash of enemy nuclear weapons, was never used for that purpose. Instead, it was used as the outermost visor by astronauts in the peaceful exploration of the moon and space.

Laser Eye Protection

Lasers (light amplification by stimulated emission of radiation) produce monochromatic, coherent, collimated light. The laser beam diverges little, so that the energy of the beam decreases only minimally with increasing distance from the source. Laser energy is capable of severely injuring tissue in the eye that absorbs the beam energy. For example, Argon (480 nm), frequency-doubled YAG (532 nm), ruby (693 nm), neodymium (1,064 nm) lasers can injure the retina and choroid because these tissues absorb these wavelengths. Laser classification has been recently revised by the American National Standards Institute standard Z-136.1 as follows (110):

Laser Class	*Allowed Continuous Wave (CW) Laser Power*
Class 1	40 μw for blue and 400 μw for red
Class 1M	Same as class 1
Class 2	1 mW
Class 2M	Same as class 2
Class 3R (visible)	5 mW
Class 3R (nonvisible)	5 times class 1
Class 3B	500 mW
Class 4	Not limited

The military applications of lasers are increasing in the areas of target ranging and illumination. Pilots themselves are not usually at hazard from their own laser beams, but technicians and others working with such instruments should wear protective goggles or visors with an optical density that is considered safe at the laser wavelength being employed. The laser itself may be used as a weapon. Here it would be helpful if one knew the threat and used a filter to protect from that waveband. Ideally, an agile filter would be in the open state but close down when struck by a laser beam. Unfortunately, this type of protection is as yet not available. Another area of interest especially for aviation is the use of lasers around aiports. The International Civil Aviation Organization (ICAO) recently adopted an international standard that controls lasers emitted in and around international airports (111). Those restrictions were based on earlier FAA limitation established to protect U.S. airports from laser beam intrusions (Figure 14-32). The medical management of laser eye injuries is fully covered in a USAFSAM technical report, TR-88-21 (112). Injuries to the external eye, cornea, and lids can be treated. Retinal injuries affect vision, depending on the energy density absorbed by the retina and, more importantly, the location of the injury on the retina. A direct hit to the fovea markedly reduces central vision and is permanent, with little recovery of function. Other safety factors should also be considered, such as educating the worker in laser safety, not looking at the laser beam, examining for reflective materials in the laboratory or shop, posting warning signs, and operating a laser in well-lit rooms when possible (small pupils). Laser-safe working distances, the selection of protective materials, and safety programs are becoming quite complicated and involved for the flight surgeon to manage alone. One should have help from a bioenvironmental engineer or health physicist when possible.

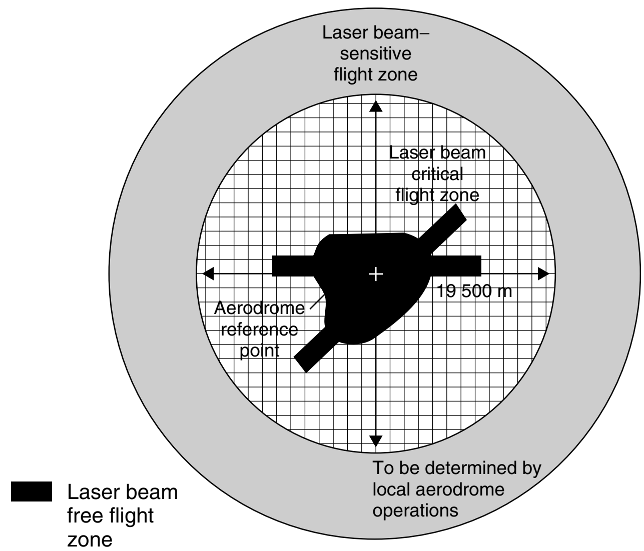


FIGURE 14-32 Protected flight zones.

The flight surgeon or aeromedical examiner, however, is responsible for setting up and performing ocular surveillance programs. Minimally, the examiner should give laser workers complete ocular examinations before they begin their assignments or employment. This should include a distance and near-central visual acuity examination, both corrected and uncorrected, an Amsler grid examination, color vision and an ophthalmoscopic examination of the fundus, with special attention to the fovea (any anomalies of the fundus should be meticulously recorded or a retinal photograph taken). A similar examination should be performed at the termination of the assignment or employment. Annual ocular examinations are not considered necessary; however, anyone working with lasers who has an ocular complaint or claims to have been injured by a laser should be examined and the complaint evaluated (113).

As stated at the beginning of this chapter, vision plays the most important role in data gathering for humans; anything affecting vision is significant for the aviator. The flight surgeon and aeromedical examiner who care for aviators and attempt to increase their effectiveness should pay special attention to the vision and visual systems of aviators.

Instantaneous, clear vision assures us of receiving uncluttered and accurate visual data into our mental computers. The integrating and processing of this information after its reception is in the domain of the central nervous system and is enhanced by training and education of the aviator. If inaccurate or incomplete visual information were received, however, we would almost be assured of failing to perform the task. With the time element for decision making becoming ever shorter in modern aviation, there is added impetus to look carefully at the visual system.

This chapter examined the physical, physiologic, medical, and bioengineering aspects of vision. With visual selection and enhancement by visual aids, the aviator's visual range has been extended, thereby giving more time for reaction and decision making. After selecting aviators with exceptional visual capabilities, it is important to employ the techniques for maintaining and protecting their vision and visual apparatus so that they enjoy full flying careers. Ophthalmology and the other visual sciences are now complex, scientific specialties. This chapter, however, has attempted to give information and data in a manner that is understandable and useful for all physicians and others interested in the subject.

REFERENCES

1. Wilmer WH, Berens C. The eye in aviation. *Office of the director of air service. Aviation medicine in the Army Expeditionary Forces (AEF)*. Washington, DC: Government Printing Office, 1920.
2. Duke-Elder SS. *System of ophthalmology, volume V: ophthalmic optics and refraction*. London: Henry Kimpton, 1970:81.
3. Pitts DG, Tredici TJ. The effects of ultraviolet on the eye. *Am Ind Hyg Assoc J* 1971;32:235.
4. Moses RA, Hart WA Jr. *Adler's physiology of the eye: clinical applications*. St. Louis: Mosby, 1987:561–582.
5. Campbell FW, Maffei L. Contrast and spatial frequency. *Sci Am* 1974;240:30–38.
6. Mannis MJ. Making sense of contrast sensitivity testing—has its time come? [Editorial]. *Arch Ophthalmol* 1987;105:627–629.
7. Randel HW, ed. *Aerospace medicine*, 2nd ed. Baltimore: Williams & Wilkins, 1972:594–595.
8. Dohrn RH. *Aircraft instrument and cockpit lighting by red or white light*. Conference proceedings. Springfield: Advisory Group for Aerospace Research and Development (AGARD)/North Atlantic Treaty Organization (NATO), 1967.
9. Mims JL III, Tredici TJ. Evaluation of the Landolt ring plaque night vision tester. *Aerosp Med* 1973;44:304–307.
10. Miller RE II, Tredici TJ. *Night vision manual for the flight surgeon*. Brooks Air Force Base, Texas: AMD, AL-SR-1992-0002, August, 1992.
11. Pitts DG. *Visual illusions and aircraft accidents*. Brooks Air Force Base, Texas: United States School of Aerospace Medicine, SAM-TR-67-28, 1967.
12. Luria SM. Chapter 2.3. Environmental effects on color vision. *Color in electronic displays*. Waddel and Post, 1992; 175–187.
13. Mertens HW, Milburn NJ. Performance of color-dependent air traffic control tasks as a function of color vision deficiency. *Aviat Space Environ Med* 1996;67(10):919–927.
14. Dain SJ, Honson VJ. Selection of an optimal light source for the FM 100- hue test, colour vision deficiencies IX. *Modern problems in ophthalmology*. Dordrecht: Kluwer Academic Publishers, 1989.
15. Van Everdingen J, Smith VC, Pokorny J, et al. Sensitivity of tritan screening tests as evaluated on normals at reduced levels of illumination. *Colour vision deficiencies X*. Dordrecht: Kluwer Academic Publisher, 1991:167–175.
16. Lakowski R, Oliver K. Modern industrial lighting and the protanope. *Mod Probl Ophthalmol* 1978;19:105–109, Karger, Basel.
17. Vola JL, Leprince G, Cornu L, et al. The 100 hue and mesopic level. *Mod Probl Ophthalmol* 1978;19:67–70, Karger, Basel.
18. Middleton WEK, Mayo EG. The appearance of colors in twilight. *J Opt Soc Am* 1952;42:116–121.
19. Sloan LL. A quantitative test for measuring degree of red-green color deficiency. *Am J Ophthalmol* 1944;27g:941–947.
20. Wyszechi G, Stiles WS. *Color science*. New York: John Wiley and Sons, 1982.
21. Pokorny J, Smith VC, Verriest G, et al. *Congenital and acquired color vision defects*. New York: Grune & Stratton, 1979.
22. Wright WD. The characteristics of tritanopia. *J Opt Soc Am* 1952;42:509.
23. Linksz A. *An essay on color vision and clinical color-vision tests*. New York and London: Grune & Stratton, 1964.
24. Lakowski R. Theory and practice of color vision testing. *Br J Ind Med* 1969;26(3):173–189.
25. Whilans MG, Allen MJ. Color defective drivers and safety. *Optom Vis Sci* 1992;69(6):463–466.
26. Smith DP. The assessment of acquired dyschromatopsia and clinical investigation of the acquired tritan defect in dominantly inherited juvenile. *Am J Optom Arch Am Acad Optom* 1972;49(7):574–588.
27. Lyle WM. Drugs and conditions which may affect color vision part I. *J Am Optom Assoc* 1974;45(1).
28. Lyle WM. Drugs and conditions which may affect color vision part II-diseases and conditions. *J Am Optom Assoc* 1974;45(1): 47–60.
29. National Transportation Safety Board. *Aircraft Accident Report NTSB/AAR-04/02*. Washington, DC, June, 2004.
30. Rowland LS. *A lantern for measuring chromatic thresholds*. Project 97 Report No 1. Randolph Field, Texas: AAF School of Aviation Medicine, Dec 1942.
31. Rowland LS. *Selection and validation of tests for color vision—the color threshold lantern as a quantitative test for red-green color deficiency*. Project 137 Report No 5. Randolph Field, Texas: AAF School of Aviation Medicine, Oct 1943.
32. Sloan L. A quantitative test for measuring degree of red green color deficiency. *Am J Ophthalmol* 1944;27:941–947.
33. Rowland LS. *Selection of color vision tests for the Army Air Forces: a review of studies made at the AAF School of Aviation Medicine*. Project 393 Report No 1. Randolph Field, Texas: AAF School of Aviation Medicine, Jun 1945.
34. Farnsworth D, Foreman P. *A brief history of lanterns for testing color sensation and description of the essential principles*. Color Vision Report No 11. BuMed Project X-457 (Av-241-k), 15 April 1946.
35. Farnsworth D, Foreman P. *Development and trial of New London Navy lantern as a selection test for serviceable color vision*. Color Vision Report No 12. BuMed Project X-457 (Av-241-k), 6 May 1946.
36. Cole BL, Vingrys AJ. Who fails lantern tests? *Doc Ophthalmol* 1983;55:157–175.
37. Grether WF, Connell SC, Bjornstad JM. *Experimental evaluation of the New London Navy lantern for testing color perception*. Memorandum Report MCREXD9-694-21B. Engineering Division, Air Materiel Command, Mar 1949.
38. Schmidt IS. *Comparative evaluation of the New London Navy lantern for testing color perception*. Project Report 21-29-009.

Randolph Field, Texas: USAF School of Aviation Medicine, Aug 1951.
39. Cole BL, Vingrys AJ. A survey and evaluation of lantern tests of color vision. *Am J Optom Physiol Opt* 1982;59(4):346–374.
40. Cole BL, Maddocks JD. Can clinical colour vision tests be used to predict the results of the Farnsworth lantern test? *Vision Res* 1998;38:3483–3585.
41. Kinney JS, Paulson HM, Beare AN. The ability of color defectives to judge signal lights at sea. *J Opt Soc Am* Jan 1979;69(1).
42. Zentner AB. A proposal for a diagnostic colour vision standard for civil airmen. *Aviat Space Environ Med* 1988;59:770–775.
43. Cole BL, Lian KY, Lakkis C. Color vision assessment: fail rates of two versions of the Farnsworth lantern test. *Aviat Space Environ Med* Jun 2006;77(6).
44. Birch J, Dain SJ. Performance of red-green color deficient subjects on the Farnsworth lantern (FALANT). *Aviat Space Environ Med* Jan 1999;70(1).
45. Paulson HM. *The performance of the Farnsworth lantern at the Submarine Medical Research Laboratory and in the field from 1955 to 1965*. Report No 466. Bureau of Medicine and Surgery, Research Work Unit MF022.03.03.9017.01, Jan 1966.
46. Hovis JK, Oliphant D. Validity of the Holmes-Wright Lantern as a color vision test for the rail industry. In: Mollon JD, Cavonius CR, eds. *Vision Research International Color Vision Society*. International Color Vision Society. 1998:3487–3491.
47. Forsey SD, Lane JC. *A comparison of seven tests of colour-vision. Aviation Med Memo No 19*. Dept Civil Aviation, Commonwealth of Australia, 1956.
48. Barbur JL, Harlow AJ. Colour vision testing using spatiotemporal luminance masking: psychophysical and pupillometric methods. In: Drum B, ed. *Colour vision deficiencies XI: proceedings of the Eleventh Symposium of the International Research Group on Colour Vision Deficiencies, Sydney Australia June 21–23, 1991*. Dordrecht: Kluwer AcademicPublishers 1993:417–426.
49. Barbur JL, Harlow AJ, Plant GT. Insights into the different exploits of colour in the visual cortex. *Proc Biol Sci* 1994;258:327–334.
50. Rodriguez-Carmona ML, Harlow JA, Walker G, Barbur JL. The invariability of normal trichromatic vision and the establishment of the ''normal'' range. *Proceedings of 10th Congress of the International Colour Association*. Granada, 2005;979–982.
51. Seshadri J, Christensen J, Lakshminarayanan V, Bassi CJ. Evaluation of the new web-based ''colour assessment and diagnosis'' test. *Optom Vis Sci* 2005;82(10).
52. Rabin J. Cone-specific measures of human color vision. *Invest Ophthalmol Vis Sci* 1996;37(13):2771–2774.
53. Rabin J. Quantification of color vision with cone contrast sensitivity. *Vis Neurosci* 2004;21(3):483–485.
54. Menu JP, Ivan DJ, et al. *Operational colour vision in the modern aviation environment.* Report of the NATO Advisory Group on Aeromedical Research and Development RTO-TR-16 AC/323(HFM) TP/6; ISBN: 92-837-1026-6.
55. Adams AJ. Chromatic and luminosity processing in retinal disease. *Am J Optom Physiol Opt* 1982;59:954–960.
56. Adams AJ, Rodic R, Husted R, et al. Spectral sensitivity and color discrimination changes in glaucoma and glaucoma-suspect patients. *Invest Ophthalmol Vis Sci* 1982;23:516–524.
57. Greenstein VC, Hood DC, Ritch R, et al. S (blue) cone pathway vulnerability in retinitis pigmentosa, diabetes and glaucoma. *Invest Ophthalmol Vis Sci* 1989;30:1732–1737.
58. Lanum J. The damaging effects of light on the retina empirical findings, theoretical, and practical implications. *Surv Ophthalmol* 1978;22:221.
59. Applegate RA, Adams AJ, Cavender JC. Early color vision changes in age-related maculopathy. *Appl Opt* 1987;26(6):1458–1462.
60. Sperling HG. Intense light hazards in ophthalmic diagnosis and treatment. *Vision Res* 1980;20:1033–1203.
61. Hansen E. The disturbance of colour vision after sunbathing. In: G Verriest, ed. *Colour vision deficiencies V*. Bristol, England: Adam Hilger Ltd, 1980.
62. Tso M, Wordford MS. Effect of photic injury on the retinal tissue. *Ophthalmology* 1983;90:952–963.
63. Fishman GA. Ocular phototoxicity: guidelines for selecting sunglasses. *Surv Ophthalmol* 1986;31(2):119–124.
64. Ham WT, Ruffolo HA, Mueller HA, et al. The nature of retinal radiation damage: dependence in wavelength, power level, and exposure time. *Vision Res* 1980;20:1105–1111.
65. Sliney D, Wolbarsht M. *Safety with lasers and other optical sources: a comprehensive handbook*. New York: Plenum Press, 1982:251–252.
66. Jaeger W, Krastel H. Colour vision deficiencies caused by pharmacotherapy. *Colour vision deficiencies VIII*. Martinus Nijhoff/Dr W. Junk Publishers, 1987.
67. Fraunfeld FT, Meyer SM. *Drug induced ocular side effects and drug interactions*. 3rd ed. London: Lea & Febiger, 1989.
68. Lakowski R, Morton A. Acquired colour losses and oral contraceptives. *Mod Prob Ophthal* 1978;19:314–318.
69. Mahon LE, Jacobs RJ. Electronic flight information displays and colour defective observers. *Clin Exp Optom* 1994;74:196–203.
70. Cole BL, MacDonald WA. *Defective colour vision can impede information acquisition from color coded video displays.* Victorian College of Optom, Report No. 3 to the Dept. of Aviation Melbourne, Australia, 1986.
71. Cole BL, MacDonald WA. Defective colour vision can impede information acquisition from redundantly colour coded video displays. *Ophthalmic Physiol Opt* 1988;8:198–210.
72. Mertens HW, Milburn NJ. *Performance of color-dependent tasks of air traffic control specialists as a function of type and degree of color vision deficiency*. Report DOT/FAA/AM-92/28. Washington, DC: Federal Aviation Administration, Office of Aviation Medicine, 1992.
73. Christ RE. Review and analysis of color coding research for visual displays. *Hum Factors* 1975;17:542–570.
74. Bergman H, Duijnhouwer F. Recognition of VDU presented colours by colour defective observers. In Proc, 24th *Annual Meeting Human Factors Soc*, The Human Factors Soc, Santa Monica, 1980:611–615.
75. Andresen S. *Signal recognition performances of color vision normals and color defectives related to work at a multicolor screen*. Bremen, Kiel, 1992.
76. Mertens HW, Milburn NJ. Validity of clinical color vision tests for air traffic control. *Aviat Space Environ Med* 1998;69(7):666–674.
77. Kuyk TK, Veres IIIJG, Lahey MA, et al. The ability of protan color defectives to perform color-dependent air traffic control tasks. *Am J Optom Physiol Opt* 1986;63:682–686.
78. Cole BL. The handicap of abnormal color vision. *Clin Exp Optom* 2004;87:4–5.
79. Welsh KW, Vaughan JA, Rasmussen PG. Aeromedical implications of the X-chrome lens for improving color vision deficiencies. *Aviat Space Environ Med* 1979;50:249.
80. Wulfeck JW, Weisz A, Raben M. *Vision in military aviation*. WADC Technical Report 58–399. Wright Air Development Center, Wright-Patterson AFB, Ohio, 1958.
81. Provines WF, Kislin B, Tredici TJ. *Multiple images in the F/FB-111 aircraft windshield: their generation, spatial localization, and recording*. SAM-TR-77-32, Brooks Air Force Base, Texas: United States Air Force School of Aerospace Medicine, 1977.
82. Sanders DR, Koch DD. *An atlas of corneal topography*. Thorough-fare: Slack, Inc, 1993.
83. Peters DR, Green RP Jr. The pigmentary dispersion disorder in USAF aviators. *Aviat Space Environ Med* 1992;63:1049–1053.
84. American Academy of Ophthalmology. American Academy of Ophthalmology Optic nervehead and retinal fiber layer analysis. *Ophthalmology* 1999;106(7).

85. Tredici TJ. Screening and management of glaucoma in flying personnel. *Mil Med* 1980;145:1.
86. Serle JB, Podos SM. New therapeutic options for the treatment of glaucoma. *Focal Points* 1999;XVII(5).
87. Green RP Jr, Carlson DW, Dieckert JP, et al. Central serous chorioretinopathy in US Air Force aviators: a review. *Aviat Space Environ Med* 1988;59:1170–1175.
88. Carlson DW, Green RP Jr. The career impact of keratoconus on Air Force aviators. *Am J Ophthalmol* 1991;112:557–561.
89. Tredici TJ, Stern C, Burroughs J, Ivan DJ. Poster: cataract surgery in USAF pilots. American Academy of Ophthalmology annual meeting. Atlanta, 1995.
90. Dennis RJ, Apsey DA, Ivan DJ. Aircrew soft contact lens wear: a survey of USAF eye care professionals. *Aviat Space Environ Med* 1993;64:1044–1047.
91. Tredici TJ. Role of orthokeratology: a perspective. *Ophthalmology* 1979;86:698.
92. Rowsey JJ, Balyeat HD. Preliminary results and complications of radial keratotomy. *Am J Ophthalmol* 1982;93:437.
93. Waring GO III. *Focal points: clinical modules for ophthalmologists*. Vol. 10, No. 5. San Francisco: American Academy of Ophthalmology, 1992.
94. Waring GO III. Radial keratotomy for myopia. In: *Focal points: clinical modules for ophthalmologists*. Vol. 10, No. 5. San Francisco: American Academy of Ophthalmology, 1992.
95. Kezerian GM, Stonecipher KG. Comparison of the IntraLase femtosecond laser and mechanical keratomes for laser *in situ*keratomileusis. *J Refract Surg* 2004;30:804–811.
96. Durrie DS, Kezerlan GM. Femtosecond laser versus mechanical keratome flaps in wavefront-guided *in situ*keratomileusis. *J Cataract Refract Surg* 2005;31:120–126.
97. Landau D, Levy J, Solomon A, et al. Traumatic corneal flap dislocation one to six years after LASIK in nine eyes with a favorable outcome. *J Refract Surg* 2006;22(9):884–889.
98. Guttman C, Talsman J, McDonald M. Can future patients expect to see better than 20/20? *Ophthalmol times* 2001;26(5):21.Mar
99. Vukich JA, Ticlittom ISG. U.S. Food and Drug Administration clinical trial of the implantable contact lens for moderate to high myopia. *Ophthalmology* 2003;110:255–266.
100. Rapuano CJ, Sugar A, Kolch DD, et al. Intrastromal corneal ring segments for low myopia. *Ophthalmology* 2001;108:1922–1928.
101. Holmes-Higgin DK, Burris TE. Corneal surface topography and associated visual performance with Intacs for myopia: phase III clinical trial results. The Intacs Study Group. *Ophthalmology* 2000;107:2061–2071.
102. Ivan DJ, Tredici TJ, Perez-Becerra J, et al. Photorefractive keratectomy (PRK) in the military aviator: an aeromedical perspective. *Aviat Space Environ Med* 1996;67(8):770–776.
103. Diamond S. Excimer laser photorefractive keratectomy (PRK) for myopia—present status: aerospace considerations. *Aviat Space Environ Med* 1995;66:690–693.
104. Ohlsson J, Villareal G. The "20/20" standard. *Acta Ophthalmol Scand* 2005;83(4):487–491.
105. Velasco e Cruz AA. Historical roots of 20/20 as a (wrong) standard value of normal visual acuity. *Optom Vis Sci* 1990;67:661.
106. Frisen L, Frisen M. How good is normal visual acuity? A study of letter acuity thresholds as a function of age. *Albrecht Von Graefes Arch Klin Exp Ophthalmol* 1981;215:149–157.
107. Miller D. *Optics and refraction*. New York: Gower Medical Publishers, 1991:10–13.
108. Welsh KW, Miller JW, Shacklett DE. An acceptability study of photochromic lenses. *Optom Wkly* 1976;21:16–21.
109. Byrnes JA, Brown DVL, Rose HW, et al. Chorioretinal burns produced by an atomic flash. *Arch Ophthalmol* 1956;55:351.
110. American National Standards Institute. *American national standards for the safe use of lasers*. New York: American National Standards Institute, ANSI Z136.1 1976.
111. International Civil Aviation Organization. *Manual on laser emitter and flight safety*, First Edition. International Civil Aviation Organization. 2003.
112. Green RP Jr, Cartledge RM, Chaney FE, Menendez AR. *Medical management of combat laser eye energies*. USAFSAM-TR-88-21, 1988.
113. Air Force Occupational Safety and Health. *Air Force Occupational Safety and Health (AFOSH) Standard 161-10, Health Hazards Control Laser Radiation*. Washington, DC: Department of the Air Force, 1980:23–24.

RECOMMENDED READINGS

Gregory RL. *Eye and brain*, 4th ed. Princeton: Princeton University Press, 1990.
Lerman S. *Radiant energy and the eye*. New York: Macmillan, 1980.
Michaels DD. *Visual optics and refraction*. St Louis: Mosby, 1985.
Newell FW. *Ophthalmology, principles and concepts*, 8th ed. St Louis: Mosby–Year Book, 1996.
Pitts DG, Kleinstern RN. *Environmental vision*. Boston: Butterworth-Heinemann, 1993.
Yanoff M, Duker JS. *Ophthalmology*. St Louis: Mosby, 1999.

CHAPTER 15

Otolaryngology in Aerospace Medicine

James R. Phelan

INTRODUCTION

The ear, nose, and throat (ENT) area, like many others, contains several structures that must be functioning properly for the safe performance of flying duties. It is safe to say that when these functions are impaired or exaggerated, such as when the Eustachian tube is blocked or the labyrinth is sending conflicting signals to the central nervous system (CNS), an aircrew member may become suddenly and completely incapacitated. Some ENT conditions may be permanently disqualifying for flight, but most are either self-limited or reversible with proper treatment. Fortunately, it is uncommon for a trained aviator or an astronaut to be permanently grounded as a result of an ENT illness or condition.

Functional Anatomy and Physiology

The Ear and Hearing

Because adequate hearing is essential to the safe operation of any aircraft or spacecraft, it is of the utmost importance that existing hearing be preserved, and that any treatable hearing loss be considered for treatment. For any sound to be heard normally, a complex chain of events must happen, and any interruption in this chain can result in diminished or absent hearing.

Perception of sound involves both physical and electrochemical processes. It begins with the collection of sound pressure waves by the external ears, which provide a small amount of amplification, and more importantly, localization of sounds in space. Localization is possible because sound waves reach each ear at slightly different times, at slightly different volumes, and with slightly different resonances, depending on the position of the head. Tiny movements of the head help in this localization. Much of this localization is lost when wearing headsets, although sophisticated acoustic engineering can restore some of this localization. Once the sound waves have entered the gently curved external ear canal, they impinge on the tympanic membrane (TM) causing physical vibration of the TM and its three attached middle ear ossicles. The malleus is embedded within the midportion of the TM, the incus provides a bridge from the malleus to the stapes, and the stapes inserts into the oval window, which is the middle ear's interface with the inner ear. The area of the TM is approximately 20 times the area of the oval window, providing mechanical amplification of the sound waves. In addition, the ossicles themselves are levered in such a way as to provide further mechanical advantage to the system. Absence of the TM and/or ossicles invariably leads to a rather large conductive-type hearing loss. Although this may occur congenitally, in the trained aircrew it is usually the result of trauma, infection, or surgery.

At the oval window, the stapes footplate is in direct contact with the perilymph of the inner ear and sound vibrations are transmitted through this fluid to the neurosensory hair cells of the cochlea. Each of these cells is ciliated, and the cilia deform in response to the propagating vibratory wave. The amplitude of this wave is interpreted as volume, whereas the frequency is sensed as pitch. Different pitches are sensed by hair cells in different areas of the cochlea. As the cilia deform, neurotransmitters are released and action potentials are generated. These action potentials are carried to the CNS by the eigth cranial nerve through the brainstem to the temporal cortex, where they are interpreted as sound.

Balance

The sense of balance is achieved through a complex interaction between the eyes, the cerebellum, skin, muscle and joint proprioceptors, and the vestibular portion of the inner ear. When any one of these components is compromised, it is possible to compensate for its loss. For instance, if the eyes are closed but all other balance systems are normal, we can usually remain upright and even walk fairly normally. However, when two or more systems are impaired, the sense of balance can be seriously degraded. This discussion will only focus on the balance function of the inner ear.

Each inner ear has two types of "accelerometers," the ampullae of the semicircular canals, which sense angular acceleration and the maculae of the utricle and saccule that sense linear acceleration. There are three semicircular canals in each ear, oriented at right angles to each other, allowing them to sense acceleration in three different axes. These axes are analogous to the three basic axes of aircraft maneuvering, yaw, pitch, and roll. The opposite ear senses the same motions in a complementary manner, and together they can sense complex combinations of these three basic motions. There are ciliated cells within the ampullae, and they deform in response to the motion of fluid within the canals, thereby generating action potentials that are then sensed as motion. However, the canals have a rotational threshold of approximately 3 degrees/s. Motion below this threshold is not sensed, which has important implications for aviation. For example, it is possible for an aviator to have the aircraft slowly roll and descend without him or her being aware of any sensation whatsoever. If this occurs in instrument meteorologic conditions and the gauges have not been monitored carefully, control of the aircraft may be lost due to spatial disorientation and controlled flight into terrain.

Linear acceleration, such as felt during a catapult launch or when extending the speed brake, is sensed by the utricle and saccule. Gravity is also a linear acceleration, although we are generally unaware of it unless its forces on the body are altered or eliminated such as during aerobatics or space flight.

Inner ear inputs to the vestibular system help control the many activities in which we engage, from getting out of bed in the morning to performing competitive gymnastics. Through these inputs, the semicircular canals help in keeping our eyes focused on a target when our head is moving, and they help prevent falling to the ground when we stumble. However, the aerospace environment can challenge these inner ear functions, so it is important to be aware of their limitations.

The Nose and Sinuses

The nose and the paranasal sinuses may be considered as a unit because normal sinuses are aerated, and they communicate directly with the air in the nasal cavity. Both structures are lined with ciliated mucosa that normally produces a thin mucus blanket that is slowly transported by ciliary action toward the nasopharynx where it is eventually swallowed. Although there is no obvious reason why sinuses exist, the nose itself has four clearly important functions in addition to allowing the passage of air: humidification, warming, cleansing of inspired air, and olfaction. In addition, the nose and sinuses together lend a characteristic resonance to speech that can change temporarily during the course of a sinonasal infection. Within the nasal cavity, there are three pairs of turbinates: inferior, middle, and superior. The inferior turbinates are highly vascular and can readily engorge with blood in response to inflammatory or autonomic stimuli. The middle turbinates are smaller and not quite as vascular, but are also capable of some swelling, and can develop polypoid degeneration in response to assorted irritants such as nasal allergens or chronic purulent sinus drainage. Because of their location near the ostia of the maxillary, frontal, and anterior ethmoid sinuses, swelling of the middle turbinates has a greater effect on sinus aeration and drainage than does swelling of the inferior turbinates, which contribute more to symptomatic congestion. The superior turbinates are small, difficult to see on routine examination, and rarely play a role in nasal or sinus obstruction. All of the turbinates taken together create a large surface area, allowing for inspired air to interact more thoroughly with the mucosa.

As air enters the nose and reaches the turbinates, its flow becomes somewhat turbulent. This allows for maximum contact between air and mucosa, enhancing the above-mentioned nasal functions. The normal rhythmic back-and-forth nasal airflow also creates a small amount of airflow into and out of the sinuses, thereby maintaining normal oxygen partial pressures within. Well-aerated sinuses with functioning ciliated mucosa are not prone to infection. In contrast, interruption of this airflow coupled with compromise of ciliary action can lead to mucus stagnation and an increased likelihood of infection. Conditions that cause injury to the mucosa and/or blockage of the ostia and nasal cavity favor the development of bacterial sinusitis. These include viral upper respiratory infections (URIs), significant allergic rhinitis (particularly, when accompanied by nasal polyps), overuse of topical decongestant sprays, and even inhalation of excessively dry air. Although decongestants and dry air do not by themselves cause sinusitis, they can lead to thickening and crusting of nasal mucus secretions, which can hinder the migration of the mucus blanket, thereby increasing the chances of stagnation and bacterial growth. It is important to maintain adequate hydration when exposed to very dry air, and the additional use of saline nasal sprays or gels can be helpful.

Swallowing and the Eustachian Tube

The Eustachian tube is the only route for air to enter and leave the middle ear when the TM is intact. The Eustachian tube also provides a drainage route for mucus secreted by the middle ear mucosa, and because it is normally closed at rest it protects the middle ear from pharyngeal secretions and dampens the perception of one's own voice. Normal transmission of sound from the TM and ossicles to the oval window depends on a middle ear filled with air at ambient pressure, and any change from that state can result in conductive hearing loss. The air cells within the mastoid bone communicate with the middle ear and provide an additional volume of air that can briefly act as a buffer against potentially painful changes in ambient pressure, but the Eustachian tube is always the primary route for pressure equalization. Middle ear ventilation usually happens without our awareness, because the Eustachian tube opens chiefly by contraction of the tensor veli palatini muscle during swallowing and yawning; this opening allows a small volume of air to pass. This ventilation must be done periodically, for if the Eustachian tube does not open, gases in the middle ear will equilibrate with lower partial-pressure gases in the mucosa, causing a slow decrease in middle ear pressure, and possibly leading to an effusion. As the ambient pressure decreases during ascent in an aircraft, the middle ear pressure becomes relatively higher, and the Eustachian tube in almost every case will vent passively. This venting can be facilitated by a quick swallow or yawn, but it is generally not necessary. However, during descent, when increasing ambient air pressure begins to push the TM inward, the Eustachian tube must be actively opened by performing some type of maneuver. If nothing is done, significant pain invariably results, and if the pressure differential is high enough a middle ear effusion will occur. This will be discussed further in the section **Barotitis Media**.

The Upper Airway

The oral and nasal airways are equipped with structures that can increase resistance to inhalation and exhalation, thereby helping to maintain lung compliance. The primary resistive structures during normal respiration in the absence of adenotonsillar hypertrophy are the turbinates, with the soft palate playing a lesser role. Autonomic nervous system control of the vessels within the turbinates produces alternating engorgement and shrinkage of the turbinates, shifting nasal resistance from side to side every 1 to 5 hours. We are rarely aware of this cycling because total nasal resistance remains fairly constant. However if there is unilateral nasal obstruction from a neoplasm, polyp, or septal deviation, the total resistance will increase when the turbinates on the "good" side are engorged, leading to symptomatic obstruction and even mouth breathing. Such upper airway obstruction can contribute to obstructive sleep apnea, a condition with great implications for aviation safety that will be discussed in a subsequent section.

THE FOCUSED OTOLARYNGOLOGIC EXAMINATION

The ability to perform a pertinent head and neck examination is essential when evaluating aerospace personnel. A detailed evaluation, including fiberoptic endoscopy, is better left to the otolaryngologist, but with a few basic aids, an adequate basic examination can be done by almost any practitioner.

Face

Congenital facial abnormalities will often be immediately visible, and if they are not amenable to correction, may be disqualifying for aviation. For example, severe malocclusion, significant facial asymmetry, or a badly deformed nose can interfere with the wearing of the oxygen mask. Fortunately, most can be remedied surgically. Inspect and palpate the parotid areas, as asymptomatic tumors of the gland are fairly common and easy to miss.

Hearing

Virtually anyone who is applying for aerospace training or is undergoing a required periodic physical examination should get a standard screening audiogram. If the audiogram shows significant asymmetry in thresholds between ears, or if the subject complains of a unilateral loss before getting the audiogram, a tuning fork examination may give some preliminary information until a complete audiogram can be done. The 512-Hz fork is the single most useful one to keep handy, and can help differentiate between a conductive and a sensorineural loss. The simplest test to perform is the Weber, in which the fork is struck on the heel of the hand and placed at the top of the subject's forehead using moderate pressure. If the screening audiogram shows a 10 dB or greater difference between ears at 500 Hz, the fork will likely lateralize (be heard better in one ear than the other). As a rule, if it is heard louder in the ear with the greater loss, a conductive loss is presumed. If it is heard louder in the better ear, then a sensorineural loss is more likely. This can be clinically important information, as conductive losses can often be fixed. A conductive loss may be caused by a condition that can easily be handled in the clinic, such as a cerumen impaction, or it may require sophisticated otologic surgery, such as ossicular reconstruction or replacement. Sensorineural losses are not surgically repairable, although severe losses can benefit from placement of a cochlear implant. The Weber test is helpful, but certainly not diagnostic, so a complete audiogram should be done as soon as practicable.

Ear

Congenital deformities of the pinna may be associated with external canal and middle ear anomalies as well, but they are rare. Examination of the external canal and TM is more likely to reveal pathology. Because the external canal is somewhat S-shaped and runs anterosuperiorly, the pinna should be gently pulled upward and backward to straighten the canal and allow easier access for the otoscope speculum. Choose the largest speculum that comfortably fits in the cartilaginous outer third of the canal, and brace the hand holding the otoscope against the subject's head. This can prevent unanticipated motion by you or the subject from causing the speculum to go in deeper, making contact with the extremely sensitive and fragile skin of the bony medial two thirds of the canal. Cerumen or foreign bodies (which come in all sizes and shapes) may obscure all or part of the TM and should be removed in order to complete the examination. This may require specialty consultation. The normal TM is light gray in color and somewhat transparent. If pneumatic otoscopy is performed, the TM should move freely in and out while the bulb is squeezed and released. Do not squeeze too firmly, especially if the speculum is making a tight seal in the canal! Movement is more easily seen if the bulb is squeezed gently and rapidly. Lack of movement may indicate a hidden perforation or a middle ear effusion. Next, ask the subject to perform the Valsalva maneuver (detailed in a subsequent section), and look carefully for a slight but definite outward movement of the TM. Absence of visible movement is not necessarily a sign of pathology, but it does indicate the need for further evaluation, including tympanometry. Tympanometry, also known as *impedance audiometry*, can reveal the presence of significant negative middle ear pressure and effusion, both of which are indications of Eustachian tube dysfunction. A normal tympanogram is therefore reassuring when TM motion is not visualized during Valsalva.

Nose

If a head mirror or electric headlight is not available for the examination, use an otoscope with a large speculum. Look for septal deviations, markedly swollen inferior turbinates, and masses such as polyps or tumors. If the subject complains of nasal obstruction but no cause is apparent, look for inspiratory collapse of the nasal valve area just anterior to the nasal bones. If seen, ask about a history of rhinoplasty, because such collapse on normal inspiration may mean that the cartilages were weakened by surgery. Septal deviations are very common, and often cause no symptoms, so in many subjects they can be ignored. Polyps are seen as shiny yellowish or gray grape-like structures, and can range from barely visible to actually protruding from the nostrils. They usually indicate the presence of a condition that is aeromedically significant. Tumors may have ulcerations or bloody crusting. The nasal examination will be more complete if a topical decongestant is sprayed in both nostrils several minutes in advance.

Mouth and Throat

Malignant lesions in this area, particularly on the floor of the mouth and in the base of tongue, can be particularly difficult to see on a cursory examination. Be sure to lift the tongue with a wooden depressor and inspect all areas carefully, especially if the subject is a smoker or a heavy drinker. Smokeless tobacco users should have the inside of the lower lip and buccal mucosa visualized. If tonsils are present, significant asymmetry is worrisome for neoplasm. Fasciculations or deviation of the tongue may indicate neurologic disease. Although not routinely done, palpation of the back of the tongue may reveal a firm or hard area that could well be a malignancy, especially in a subject that has a neck mass. Although some tumors in the oral and pharyngeal area are frankly exophytic, many are ulcerated or appear as white or red patches. Suspicious lesions must be biopsied as soon as possible. Persistent hoarseness or pain is an indication for specialty referral.

Neck

Palpate the neck for masses or tenderness, paying special attention to the thyroid, lymph nodes, and submandibular salivary glands. Have the subject swallow while observing the thyroid for mobile masses (ideally with the light source shedding tangential light on the neck), then palpate the gland before and during swallowing. Many examiners prefer to stand behind the subject while palpating with both hands. Palpable or visible masses anywhere in the neck must be evaluated further. Listen for bruits over the carotid arteries.

Skin

Recreational and occupational sun exposures carry a real risk of skin malignancy, so examining the skin of the head, face, and neck is important. The most susceptible areas include the ears, nose, and lips. Early detection is vital, as small lesions may be easily cured. A magnifying glass can help in the examination. Specialty referral is advised for any suspicious lesion.

OPERATIONALLY SIGNIFICANT DISORDERS

Ear

Noise-Induced Hearing Loss

Progressive hearing loss due to occupational noise exposure is a widespread and serious problem, resulting in individual impairment and costing the government and industry hundreds of millions of dollars a year in compensation payments; much of it is preventable. The U.S. military services mandate enrollment in a hearing conservation program for all members who are expected to be exposed to high levels of noise during their careers. The program involves periodic audiograms, education, workplace sound level measurements, and provision of personal hearing protection. Continuous noise is more harmful than intermittent noise, and over time is more likely to impair hearing in the lower speech frequencies than is intermittent noise. Fortunately, neither type of noise causes a profound hearing loss, but they both cause early damage in the higher frequencies. Loss in these frequencies impairs speech discrimination due to muffling of consonants, and is most noticeable when there is background noise. When it is impossible to escape noise, and when engineering solutions have been maximized, hearing protection is all that is left. Those workers who are exposed to persistent loud noise, such as flight-line personnel, will usually wear double protection in the form of insert earplugs and over-the-ear muffs. Together, when worn properly, they can be fully protective during a normal working day provided ambient noise levels remain less than 125 dB, but while wearing them communication is difficult at best. Aircrew must be able to communicate in the face of high levels of noise, and when double protection is worn, maximum radio volumes may still not be adequate. Active noise reduction headsets can be quite effective at attenuating unwanted background noise, but some are bulky and all require additional electronic components. A cheaper, lighter, and equally effective solution is to use communication earplugs, which occlude the ear canal like standard soft earplugs, but they also function like music player "ear buds." Radio communications bypass the occlusive effects of the earplug and allow for clear reception at comfortable volumes, while the plug itself provides background noise attenuation.

Acoustic Trauma

This term refers to a sudden hearing loss caused by an extremely loud noise. It is not a progressive loss as seen in chronic occupational noise exposure. A gun fired close to the ear or a powerful firecracker going off nearby typically causes it. There may be a small degree of hearing recovery over a few days, but most of the loss is immediate and often permanent.

Sudden Hearing Loss (Idiopathic Sudden Sensorineural Hearing Loss)

This is a medical condition and is not caused by noise. It may develop over minutes or days. It is often noticed upon awakening, and about half of patients experience some dizziness or vertigo. Viral, vascular, and autoimmune causes, as well as internal inner ear membrane disruptions have been postulated and investigated without definitive answers. Patients are usually middle-aged or younger, and many recover most or all of the lost hearing within weeks. The only treatment that has yielded data showing a positive effect is an oral steroid taper at sufficient doses over 10 days (1,2). Factors working against recovery are older age, severe initial loss, vertigo, and delay in seeking treatment. As long as no underlying disqualifying condition is diagnosed, a history of sudden hearing loss should not by itself preclude aviation duties.

Otitis Externa

Most cases of external ear infection are acute and easily treated. Chronic cases do occur, and can be quite stubborn. The responsible microbes are more likely to be bacterial than fungal, with the common culprits being *Pseudomonas aeruginosa* and *Staphylococcus aureus.* Susceptibility is increased by warm, humid weather, water immersion (particularly, in fresh-water pools), and use of cotton-tipped applicators that can abrade the skin and remove protective cerumen. Optimal treatment includes cleaning of the infected canal, irrigation with an acidifying solution, instillation of antibiotic drops, and, if the canal is too swollen to allow drops to enter, placement of a temporary wick. During the acute phase, the ear may be too tender to wear a flight helmet or a headset, and hearing may be down due to canal occlusion. Once the infection has cleared, all flying duties can resume.

Cerumen Impaction

Cerumen accumulation is common, but it is almost always harmless because it rarely results in total impaction. A large collection of hard cerumen in the ear canal can cause pain by contacting the sensitive inner bony part, and may even rest against the TM. The pain can be quite noticeable when chewing, yawning, performing the Valsalva maneuver, or trying to insert an earplug. Cerumen should be removed if the TM must be seen, or if it is causing pain or hearing loss. Removal techniques are many, and with the exception of simple instillation of dilute hydrogen peroxide, all entail some risk of canal injury or TM perforation. Irrigation should not be used if there is a history of perforation, but otherwise it is fairly safe if done gently. Use only warm water, with or without peroxide. Hot or cold water can cause a nauseating caloric reaction. Softening drops may be useful in improving the results, but difficult removals should be referred.

Acute Otitis Media

Acute otitis media (AOM) is common in very young children, but is almost never seen in adults, so it is not of significant day-to-day concern for the flight surgeon. It can arise during an URI, and is usually quite painful. The TM will be hypervascular or frankly reddened, may be bulging, and can even perforate with subsequent visible drainage from the hole. Proper treatment is a controversial topic, mainly because two of the common bacteria that cause AOM (*Streptococcus pneumoniae* and *Hemophilus influenzae*) are showing increasing levels of antibiotic resistance, probably as a result of overprescribing in questionable cases and undertreating in appropriate cases. In 2004, the American Academy of Family Physicians published guidelines that recommended, in selected cases of clinically diagnosed acute bacterial otitis media, that antibiotics may be withheld for 48 to 72 hours as long as close contact with the parents or patient is maintained and adequate pain relief is offered (3). A meta-analysis of 80 studies on the use of antibiotics in AOM (4) concluded that when looking at symptom relief, there is no evidence to support the use of one antibiotic regimen over another. There is also no consensus on duration of treatment, so specific recommendations on antibiotic choices and dosages will not be made here. Grounded aircrew may return to flying when the infection has clinically resolved and the Eustachian tube is functioning normally.

Barotitis Media

Also known as *otitic barotrauma* or *ear block*, barotitis is particularly common in aircrew trainees, but is also seen in experienced aviators who fly with colds. Pressure, typically followed by excruciating pain, begins during descent, and if the middle ear does not clear, a serohemorrhagic effusion often results. Depending on the magnitude and rate of the pressure change, the effusion may be clear to frankly bloody. Unlike in divers, TM perforations are rare in aviation personnel. Young enlisted military trainees have more problems because many of them have never experienced rapid pressure changes before and have no idea of how to equilibrate the pressure. Before their initial hypobaric chamber training, they are instructed to equilibrate by yawning, swallowing, or performing a Valsalva maneuver. Swallowing and yawning become less effective as the pressure differential between the middle ear and ambient air increases, so the trainees usually resort to the Valsalva maneuver, which is often unsuccessful even if they have physiologically normal Eustachian tubes. Failure of the Valsalva maneuver is typically due to the subject failing to transmit lung pressure to the nasopharynx where the Eustachian tube openings are. Most of the time they either have their vocal cords tightly shut or their tongue and pharyngeal muscles pushed together, effectively blocking the Eustachian tubes. The proper technique is to be sure that lung pressure is transmitted directly to the nostrils, and this can be demonstrated by releasing the nostril pinch and seeing if there is a burst of air from the nose. Once pressurized air is definitely reaching the nasopharynx and nose, then ventilation can happen. Practicing using the tensor veli palatini muscles by barely beginning a yawn will add to the chances of success. Deviating the chin and tilting the head away from the side that is not equalizing can also help. The use of a nasal decongestant spray may help, but often the only solution is to ascend in the aircraft (or altitude chamber) and try the maneuver at a higher altitude. Because the Eustachian tube can effectively "lock" when the differential pressure exceeds 80 to 100 mm Hg, ascending can reduce this differential and unlock the tube. If nothing works, it is possible to relieve the block mechanically using a pressure-generating Politzer device. These are usually available in altitude chambers, but play no role in aircraft-related barotitis. The good news is that the ear pain rarely persists once ground level is reached, and if there is an effusion, it will usually clear in a week. The decision to ground should be based on what caused the block. A subject with an URI should be grounded until the cold symptoms and any effusion are gone and the middle ear ventilates normally. A trainee who "just got behind" should be grounded until the time that he or she can demonstrate an effective Valsalva.

Because there is the possibility that straining while attempting a Valsalva can cause a drop in cardiac output and blood pressure lasting up to 20 seconds, and in older individuals can increase the potential for arrhythmias, the Toynbee maneuver is a safe alternative. It is performed by simply swallowing while pinching the nose and closing the mouth. When done with no pressure differential, it opens the Eustachian tube and actually causes a small amount of air to be pulled out of the middle ear. Because slight retraction of the TM results, the Toynbee is often used as a visual test of Eustachian tube patency. When a pressure differential does exist, equalization can occur in either direction during the short time the Eustachian tube is open.

There is another Valsalva-like technique called the *Frenzel maneuver*. It is easy to perform, and is probably safer than the Valsalva, as there is no danger of generating large pressures that could perforate the TM, blow out an inner ear window, or cause hypotension. It is done by opening the jaw, filling the mouth with air, pinching the nose, pursing the lips, and then closing the jaw while displacing air posteriorly by pushing the tongue up and back. It is important to keep the vocal cords closed, and it helps to contract the "yawning" pharyngeal muscles at the same time. Once it is done successfully, repeating it becomes almost instinctive.

Another cause of ear barotrauma is delayed barotitis or "oxygen otitis." It can happen to anyone who has been breathing high concentrations of oxygen, and is due to absorption of the oxygen in the middle ear as it equilibrates with the mucosal oxygen. It can create significant negative middle ear pressures, and is prevented by early and frequent Valsalva or swallowing. If the oxygen exposure is close to bedtime, the middle ear does not get a chance to fully equilibrate, and it is possible to awaken with ear pain and even an effusion. It may be wise to set an alarm as a reminder to clear the ears during the night.

Perilymphatic Fistula

Excessive straining, sudden marked pressure changes, or ossicular displacement can rupture either the oval or round window, resulting in a perilymph leak. Perilymph is one of two chemically dissimilar inner ear fluids, and it interfaces with both the round window membrane and the stapes footplate. Symptoms include fluctuating hearing loss, vertigo, and imbalance. Once diagnosed, symptomatic treatment should be offered and the subject put at rest with the head elevated. Specialty consultation is imperative, and if symptoms do not resolve in a few days, surgical exploration could well be advised. Before considering returning the aviator to flight, symptoms must be completely resolved without any evidence of recurrence for at least 6 months; some authorities mandate that it be a year.

Physical Qualification for Flight following Otologic Surgery

Simple repair of an eardrum perforation with a fat or fascial graft is successful in more than 90% of cases (5), and once the surgeon states that healing is complete, which may be as little as a month after surgery, flying may resume as long as Eustachian tube function is normal. More complicated surgeries, such as removal of a cholesteatoma from the middle ear or mastoid, can take a much longer time to heal, and consideration of a waiver should be delayed until then. Postoperative evaluation of hearing and Eustachian tube function is necessary, and it would not be unusual to find that, for several reasons, the hearing in the operated ear is worse than before surgery. A hearing-loss waiver would then have to be considered once the hearing loss has stabilized. There are no data to indicate that there is value in postoperative altitude chamber testing.

Surgery for otosclerosis, a disease that immobilizes the stapes footplate in the oval window, involves either fenestration of the footplate or its total or partial removal. Surgery is considered when the disease has caused a large conductive hearing loss that is problematic for the aviator. Hearing aids work well in otosclerosis because the cochlea is often normal, and all that is needed is an increase in volume. However, hearing aids can be a nuisance, and are usually unsuitable for use in the cockpit due to discomfort and sound distortion. Because volume alone can overcome the hearing loss, it would be ideal if the left-right balance of aircraft earphones could be adjusted. Unfortunately, with many systems this is not possible. During the surgery, one end of the stapes prosthesis is attached to the incus and the other end just reaches the surgical opening in the oval window, interfacing with the inner ear's perilymph. The opening is sealed with a tissue graft. In the past, it was common to remove the entire stapes, leaving a relatively large opening in the oval window. Newer techniques involving precision laser fenestration of the footplate (stapedotomy) and the fitting of a small-diameter piston into the fenestration have reduced the risk of operative inner ear damage and postoperative perilymph fistula. As a result, the previous almost universal recommendation for a year-long grounding period has been modified by some agencies, and the U.S. Navy, the U.S. Air Force, and National Aeronautics and Space Administration (NASA) now consider a 3-month period sufficient as long as hearing has stabilized and there have been no episodes of vertigo or imbalance beyond the immediate postoperative period; the U.S. Army grounds its aviators for 6 months, then restricts them to dual-pilot status for another 2.5 years. There is no universal requirement for an altitude chamber test, although the U.S. Air Force does require a chamber test with rapid decompression and rapid descent, if a complete stapedectomy was done. If the newer stapedotomy technique was done, then altitude chamber exposure will not contribute anything further to a waiver decision if the subject is able to easily clear the ear on the ground without any vertiginous sensation.

Surgical removal of an acoustic neuroma can affect hearing, balance, and facial nerve function. Detailed specialty consultation is necessary in order to make the best therapeutic decision among observation, surgery, and radiation. A waiver decision should be delayed for at least 6 months after treatment, and again would require specialty consultation. The U.S. military services have several cases of tactical jet aviators who have returned to the cockpit following acoustic neuroma surgery, so it is not necessarily a career-ending diagnosis.

Vertigo

One of the most difficult diagnoses for a flight surgeon to evaluate is that of vertigo. In medical practice, many patients will present with a simple complaint of "dizziness." When questioned further, they will variously describe the sensation as feeling "light-headed," "faint," "woozy," or "spacey" and sometimes actually state that they have vertigo. This discussion will focus on true vertigo, defined as a "hallucination of motion," which is commonly manifested as a spinning or tilting sensation. To an aviator, the word vertigo most often means spatial disorientation; because this is not an ENT diagnosis, it will not be discussed in this chapter (see Chapter 6). True vertigo, no matter how infrequent or brief the episodes are, carries the very real risk of an aviator losing control of the aircraft, and it must be evaluated thoroughly. Both an otolaryngologist and a neurologist should be consulted, and the subject grounded until a diagnosis is reached and the vertigo has completely resolved. Initial evaluation must begin with an extremely thorough history, as often the history provides the most vital diagnostic clues. Besides specialty consultation, further investigation may include blood chemistries, audiometry, posturography, oculography, CNS imaging such as magnetic resonance imaging (MRI) and MR angiography, electrocardiography, and even advanced vestibular tests such as vestibular evoked myogenic potentials (VEMPs). The VEMP and other advanced tests are not in common use and their utility as clinical tools and in making waiver decisions are not entirely clear.

A common cause of vertigo that occurs only with head position changes is benign paroxysmal positional vertigo (BPPV). The diagnosis is made by combining the classic history (delayed onset of spinning vertigo lasting less than a minute following a provocative head movement) with the physical examination (a crescendo–decrescendo pattern to the nystagmus and vertigo, clockwise or counterclockwise nystagmus, and a decrease in severity with repeated close-interval testing). The underlying condition, known as *canalithiasis*, is thought to be caused by otoconia (the calcium carbonate crystals that normally lie on top of the hair cells in the utricle and saccule) taking up a new position in one of the semicircular canals, usually the posterior. Many cases are idiopathic, but there is an underlying ear disease or a history of head trauma in a significant number of subjects, so a more extensive evaluation may be indicated. Current treatment virtually always utilizes a canalith repositioning technique, and the Epley maneuver is most commonly used (6). The technique involves slowly and precisely moving the head and body through four positions, and when properly done for a correct diagnosis of BPPV, the immediate cure rate is approximately 90%, although recurrences are possible. If the Epley maneuver fails, it can simply be repeated. After treatment, the subject is told to refrain from lying flat, and to sleep with a few pillows under the head and torso for 48 hours. Flying may resume a week or so after treatment, providing there is no evidence of vertigo or nystagmus after performing provocative head movements.

The catch-all diagnosis of labyrinthitis was once commonly made when vertigo, nausea, vomiting, and nystagmus came on rapidly. Currently, a more specific diagnosis is possible, and many of these cases are now classified as vestibular neuronitis, believed to be a viral monocranioneuropathy that involves only the vestibular portion of the eigth cranial nerve. The sudden drop in CNS input from the affected labyrinth triggers an intense perception of motion. Vestibular neuronitis, also known as *vestibular neuritis*, favors persons in the 30s to 40s and is self-limited, with most victims recovering completely in several weeks. There is evidence that a brief course of an oral steroid shortens the clinical course and hastens recovery of vestibular function (7). Acute symptoms should be treated with vestibular suppressants such as antihistamines (meclizine), phenothiazines (promethazine, prochlorperazine), or short-acting benzodiazepines (diazepam, clonazepam). Newer antiemetics such as ondansetron and granisetron, usually reserved for treating nausea and vomiting associated with chemotherapy, may be used when nothing else is effective. Neurologic consultation is helpful, especially when there are other cranial nerves involved. Once recovery is complete relapse is rare, so flying may be resumed at that time.

Ménière's disease is an idiopathic increase in pressure of the endolymph within the inner ear. It may eventually involve both ears, but it initially presents with unilateral symptoms. A classic Ménière's attack is characterized by episodic vertigo (often of very sudden onset), fluctuating hearing loss, low frequency tinnitus, and an unpleasant sensation of ear pressure. It is generally believed that the symptoms are caused by the mixing of both endolymph and perilymph due to small ruptures of internal membranes within the inner ear. This admixture has an abnormal potassium concentration that is neurotoxic to the hair cells in both the cochlea and labyrinth. The history, supplemented with complete audiometric testing, will point to the diagnosis in most cases. An oral diuretic and a low-salt diet may reduce the frequency and severity of the symptoms, but surgical sectioning of the vestibular nerve is the only method of eliminating the vertiginous episodes. Surgical sectioning is not guaranteed to be effective. After nerve sectioning, the hearing loss may progress because the underlying state of increased endolymph pressure is not changed. Middle ear instillation of gentamicin has been used for years, and can be effective in reducing vertigo episodes, but can present a significant risk to hearing. A newer technique that uses a micropump to deliver the drug to the area of the round window membrane through an indwelling microcatheter appears promising, with the added benefit of causing little or no hearing loss. Waivers are seldom granted for Ménière's disease, but they may be considered when vertigo has been absent for at least a year and the subject will not be flying solo.

Alternobaric vertigo is a curious phenomenon that occurs mainly in aviators when one middle ear vents positive pressure significantly faster than the other does or when a vigorous Valsalva maneuver clears only one ear. There is a sensation of true spinning vertigo that may last from seconds to a minute. It is unlikely to be reported if it is an isolated, very brief episode, but some subjects are prone to it, which makes their fitness to fly questionable.

Space Motion Sickness will be covered in Chapter 6. It is not due to a pathologic condition, but rather is induced at the onset of microgravity when the otolithic organs (utricle and saccule) no longer have their usual resting one-G input. Conflicting visual cues combine to create one to several days of symptoms in most space fliers. Vestibular suppressant injections are quite effective in reducing the symptoms, and research into ground-based adaptation strategies is ongoing.

Nose and Sinuses

Trauma

Sinus fractures seldom occur except in heavy blows to the face such as seen in traffic collisions. Most facial fractures can be repaired surgically, and sinus function is not likely to be affected. Nasal fractures on the other hand are quite common, and a visible deformity should be reduced by an otolaryngologist. It is extremely important to examine the inside of the nose for a septal hematoma whenever it has sustained a blow of sufficient force to cause bleeding. Hematomas obstruct both nares, and may occur even when the external nose has not been deformed. Untreated, they can lead to necrosis of the cartilaginous septum with an eventual "saddle" deformity of the nasal dorsum. A simple septal deviation without symptoms does not need to be straightened, and even those causing mild symptoms can be ignored if sinus ostial blockage is not present.

Septal perforation is a known complication of septal surgery, and if it is not causing recurrent bleeding or whistling during respiration, it does not need to be repaired. In fact, larger perforations are quite difficult to repair, so if there is no bleeding or whistling, it may be best to leave them untreated. If there are symptoms, a silicone button can be inserted to block the perforation. A perforation without a prior history of trauma or surgery should be investigated further because of the possibility that it is secondary to granulomatous disease, neoplasm, or even cocaine abuse. Benign septal perforations without recurrent bleeding should not bar the subject from flying.

Intranasal Disorders

It has been estimated that one fourth of the population have allergic rhinitis at some time during the year. Symptoms may be seasonal due to pollen exposure or perennial due to dust mite exposure. Diagnosis is straightforward when symptoms of rhinorrhea, sneezing, lacrimation, and nasal itching coincide with a particular pollen season. Less obvious cases will need to be evaluated by an allergist. Treatment can include nasal saline rinses (8), oral nonsedating antihistamines, topical nasal steroid sprays, leukotriene modifiers, and allergy immunotherapy (injections). Immunotherapy is reserved for severe or refractory cases, mainly because it must be continued for 3 to 5 years. In addition, because of the possibility of a reaction, they should only be given in a practitioner's office. All of these treatments are compatible with flying if they are effective and have no associated side effects.

Acute rhinosinusitis is typically a self-limited viral infection. During the infection, the risk of ear and sinus barotrauma is greatly increased, so grounding should continue until all symptoms have resolved. Symptomatic medications may be used, but antibiotics should be avoided unless there is evidence that the infection has become bacterial. Persistent unilateral purulent drainage, coupled with ongoing pain localized to a sinus on the same side, would be adequate evidence. Antibiotic therapy follows established guidelines (9). Flying should not resume until signs and symptoms have resolved, but if flying as a passenger is unavoidable before complete recovery, use of a topical nasal decongestant spray such as oxymetazoline is recommended to reduce the chance of sinus and ear barotrauma. Topical nasal steroids can also help in reducing nasal mucosal edema, but are slow to act and are not useful in acute situations. The practitioner should check Eustachian tube function off decongestants before returning the subject to flying duty.

Chronic rhinosinusitis is a symptomatic condition that lasts more than 3 months. It is a bacterial infection that often shows less severe signs and symptoms than acute rhinosinusitis, and aviators commonly try to fly in spite of them. Sinus barotrauma may be the first indication that a problem exists. Diagnosis requires not just a careful history and ENT examination, but a coronal CT scan as well. Initial treatment with long-term antibiotics is worth trying, but many of the subjects whose flying careers are on hold will eventually undergofunctional endoscopic sinus surgery (FESS). The surgery has a high initial return-to-flying rate, although recurrences can and do happen, so periodic reevaluation is always advised. Ideally, all postoperative subjects should undergo a functional test in a low-pressure chamber before being considered for return to flight. There is no need to go to an altitude higher than 18,000 ft, so the risk of decompression sickness during the test is minimal.

Although nasal polyps may be a manifestation of allergic rhinitis, they are equally likely to be caused by chronic infection or, less commonly, conditions such as aspirin sensitivity and cystic fibrosis. Not only can polyps cause annoying nasal obstruction, they are also likely to cause sinus barotrauma. Smaller polyps may shrink with topical nasal steroids and/or a short burst of systemic steroids, but the larger ones are best treated surgically. When polyps are seen, a coronal sinus CT is indicated because it will often show evidence of widespread sinus mucosal thickening. For this reason, endoscopic sinus surgery is usually necessary to remove areas of infection and diseased mucosa in addition to the polyps. If not removed, this mucosa will continue to hinder sinus aeration and lead to more infection and polyp formation. The decision on when to return the subject to flying, as well as the postoperative recommendations, are the same as for chronic rhinosinusitis. Solitary unilateral polyps in an otherwise normal individual should be evaluated as possible neoplasms.

Chronic nasal congestion that has no underlying allergy, infection, or intranasal mass may be due to vasomotor rhinitis. Sensitive nasal mucosa and reactive turbinates may swell at seemingly minor provocations such as temperature and humidity changes, assorted odors, nasal irritants, recumbency, and even emotional swings. Thin, clear rhinorrhea can be present as well. Topical nasal steroid sprays can help, but the symptoms can be surprisingly resistant to any treatment. A possible etiology is instability of autonomic control of the nasal vasculature. Grounding is not necessary unless there are functional problems with altitude exposure.

Rebound nasal congestion is seen in subjects who overuse nasal decongestant sprays. The worsening congestion leads to more frequent use of the medication, and eventually it becomes refractory to virtually any amount of spray, yet it continues to be used. Weaning from the decongestant is necessary, and can be aided by the use of oral decongestants, topical steroid sprays, and saline irrigations or mists. If progress is slow, a short course of an oral steroid may be added. It may be necessary to ground the aviator during the weaning period because of signs of decongestant “withdrawal” that can include significant emotional distress.

Sinus Barotrauma

Sinus barotrauma, also known as *barosinusitis* or *sinus block*, is most common in persons who fly with a URI, but as mentioned earlier, it can also be an indicator of chronic sinus problems. A sinus block in an experienced aviator who has no acute cold symptoms is an indication for further investigation. The injury is caused by increasing negative pressure within the affected sinus during descent. This relative vacuum causes rapid mucosal congestion, often with formation of a submucosal hematoma that result in extremely sharp and intensely distracting pain of sudden onset. For this reason alone it represents a hazard to safe flight. Isolated barosinusitis that happens in the course of a URI does not need an in-depth evaluation, so flying can resume once the cold symptoms are gone. In contrast, recurrent barosinusitis, even in the presence of obvious cold symptoms, should always be investigated further. The frequency of finding underlying pathology is surprisingly high.

Flight Qualification following Nasal and Sinus Surgery

It is fortunate that most nasal and sinus surgery leads to a resumption of flying, but follow-up, specifically after sinus surgery, should continue for the length of a flying career, if not lifelong. Recurrence of chronic sinusitis and polyps will lead the flyer back into familiar signs and symptoms, with the renewed risk of sinus barotrauma. Regular checkups, as frequently as every 4 to 6 months, can spot a recurrence when it is easiest to treat and when it has less chance of causing a lengthy period of grounding. Waiver recommendations should always include appropriate follow-up intervals, and if they are faithfully adhered to, there is relatively little chance of a major career interruption.

Oral Cavity, Pharynx, and Neck

Oral Cavity Conditions

The vermilion of the lower lip and the vermilion-skin border of the upper lip are prone to develop squamous cell carcinoma due to sun exposure. Because of their prominent location, most should be diagnosed early, and local excision can often be curative. Healing after treatment is rapid, and there should be only a short period of grounding, with regularly scheduled reexaminations to look for recurrences or new lesions. If the cancer has already metastasized to regional or distant lymphatics, treatment will be much more extensive, and a decision to return the subject to flying will depend on factors best evaluated by appropriate specialists.

Recurrent herpes simplex lesions commonly erupt in the area around the vermilion-skin border and are self-limited, but an initial oral herpes infection can cause a widespread mucosal outbreak that would be cause for grounding. In both cases the lesions are transmissible, so hand or mouth contact with others is unwise during the symptomatic phase. Early treatment with oral antivirals may shorten or even arrest the outbreak, and antiviral ointments can be of some help in lip lesions.

Aphthous ulcers (canker sores) can be painful out of proportion to the small area they cover. Typically, they heal within 2 weeks, but some unfortunate patients seem to produce new lesions before the old ones have healed. The etiology is uncertain and the list of suggested precipitating factors is long, including stress, oral trauma, cessation of smoking, and progesterone level fluctuations during the menstrual cycle. However, supporting evidence is scarce (10). The ulcers are small, with a yellow or gray base and a reddened border. Treatment is symptomatic, and triamcinolone in a carboxymethylcellulose paste is popular and relatively effective. Tetracycline and chlorhexidine gluconate mouth rinses also show evidence of efficacy. If pain is prominent, 20% benzocaine in carboxymethylcellulose paste can give immediate relief. Although they may assist healing, none of these preparations will prevent the next outbreak. Fortunately, grounding is rarely necessary. Large, multiple, frequent, or persistent ulcers (>3 weeks) require a more in-depth evaluation for possible underlying illnesses.

Pharyngeal Conditions

Acute pharyngitis is common during many colds, and leads to reddened mucosa, often with tender cervical lymph nodes. Most infections are viral, but if fever, malaise, and mucosal exudates are present, there is a chance that the infection is bacterial and a rapid streptococcus screen should be done. A positive screen test result for Group A β-hemolytic streptococcus indicates the need for antibiotics, but antibiotics may also be indicated when the result is negative if there is high fever, marked malaise, or necrotic-appearing tonsils.

Infectious mononucleosis due to the Epstein-Barr virus (EBV) can present as severe pharyngitis and tonsillitis with prominent cervical adenopathy. Elevated heterophile antibody titers as evidenced by a positive Monospot test, and a complete blood count that shows an abnormal number of atypical lymphocytes, help confirm the diagnosis (although the Monospot test may not become positive early in the course of the disease). More expensive EBV-specific antigen and antibody tests may be useful in determining if the infection is recent or occurred previously, but are usually not necessary. Mononucleosis is a systemic illness, with liver and spleen involvement that can cause enlargement of both organs. Liver function tests should be done, and the individual should not participate in contact sports until recovery because of the danger of splenic injury. Steroids with and without antivirals have been used in the treatment of severe symptoms, but have not been shown to be of significant benefit (11–13). Because in some cases malaise and fatigue can be prolonged, flying should be avoided until all symptoms and signs (including hepatosplenomegaly) are gone. Cervical lymph nodes may be slow to return to baseline, and if all other manifestations of mononucleosis have resolved, flying can resume.

Acute tonsillitis is often part of the usual URI-related acute pharyngitis, but occasionally the pain in one tonsil will rapidly increase, with difficulty swallowing, trismus, and voice change (the so-called hot potato voice that results from the victim trying to avoid painful tongue movements). These are the classic signs of a peritonsillar abscess, and treatment is aimed initially at draining pus from the abscess cavity. Aspiration of the cavity with a no. 18 needle can be very effective, and should be supplemented by antibiotic treatment, pain relief, and rehydration. If pus reaccumulates, the abscess cavity might require wide incision and drainage. Tonsillectomy may be done acutely in this setting. Whether a tonsillectomy should eventually be done is debatable, but in cases of recurrent tonsillitis and/or recurrent abscesses, it may be recommended. Once symptoms have resolved, the subject can return to flying.

Snoring is often regarded as a simple social problem, but bad snorers may be headed for a more serious condition known as *obstructive sleep apnea syndrome* (OSAS). Sleep apnea is seriously under-recognized, and there is frequently a long delay in diagnosis, especially in persons who sleep alone. The cardinal symptom, and the most worrisome one in anyone who drives or flies, is excessive daytime sleepiness. This is the result of fragmented and nonrefreshing sleep that comes from frequent arousals due to an intermittently obstructed upper airway. Associated symptoms are morning headache, dry mouth and throat, fatigue, irritability, and difficulty with concentration. Sufferers may gasp, snore, and have both audible and visible obstructive apneic episodes. Men are approximately twice as likely as women to have the condition, but men outnumber women by as much as 8:1 in sleep center referrals, possibly because of reluctance by women to acknowledge that they have a snoring problem. Risk factors include obstructing lesions of the upper airway, obesity [body mass index (BMI) >30], neck size greater than 17 in. regardless of BMI, older age, retrognathism, a visibly elevated tongue base, a narrowed oropharyngeal airway, and alcohol use. Any or all of these factors can contribute to obstruction of the airway, often with dramatic drops in arterial oxygen saturation. A thorough head and neck examination along with an in-depth history (and an interview with the bed partner) should be done before referring the subject to a sleep center. If untreated, OSAS can contribute to metabolic syndrome, and is known to increase the incidence of myocardial infarction, stroke, and sudden nighttime death. In the driving and flying population, mishaps from falling asleep at the controls are a real possibility. Once OSAS is diagnosed, the primary treatment is to administer continuous positive airway pressure (CPAP) during sleep using a nasal appliance. When it is used for 6 or more hours a night, it can completely reverse all symptoms and even improve the insulin resistance seen in metabolic syndrome. If CPAP is rejected for any reason, surgery, including uvulopalatopharyngoplasty (UPPP), maxillary and mandibular advancements, and tongue reduction may help, although CPAP has by far the better record of success. In rare cases, the only effective treatment is tracheostomy, which completely bypasses the obstruction but is incompatible with flying. Aviation personnel with known or suspected obstructive sleep apnea must be grounded and referred for objective evaluation, which should include polysomnography performed at a sleep center. If OSAS is diagnosed, it must be treated. If applicable, treatment should include weight loss. A return to flying should only be considered if posttreatment interviews combined with a new sleep study show that the condition has been eliminated and the patient successfully passes a maintenance of wakefulness test. There is a temptation for some subjects on CPAP to let the treatments lapse, and within days to weeks they have a return of all symptoms, so it is important to keep in close contact with them. Fortunately, most people find that CPAP makes them feel so much better that they never give a thought to quitting.

Gastroesophageal reflux disease (GERD) can have manifestations outside the esophagus such as morning hoarseness, nagging cough, sore throat, Eustachian tube, and middle ear inflammation, and even tooth enamel erosion. When it is suspected, conservative measures are initially recommended such as eating smaller meals, avoiding evening alcohol, not eating within 3 hours of bedtime, and elevating the head of the bed. These measures may be combined with oral histamine H2 receptor antagonists. Be aware that the individual may already be taking them without the practitioner's knowledge, as they have long been available without a prescription. Proton pump inhibitors have more recently become available without a prescription, and they are not recommended for use beyond 14 days without physician oversight. In some cases, surgery such as fundoplication may be recommended, but the effectiveness of surgery when antacid therapy has failed had not been conclusively demonstrated (14). The decision to allow or restrict flying depends on the severity of symptoms, and whether or not treatment is effective.

Hoarseness of acute onset is associated with viral URIs and vocal abuse. If the onset is insidious and the hoarseness is persistent, consider GERD, vocal cord lesions, and chronic smoking-induced laryngitis. Relative voice rest should be tried for a few days, but if hoarseness continues beyond 3 or 4 weeks, the larynx must be visualized by mirror or endoscope. Most benign vocal cord lesions such as polyps, nodules, edema, and hyperkeratosis can be observed or treated surgically. Nodules may regress with intensive speech therapy, and edema may resolve after stopping smoking. Lesions suspicious for carcinoma should be biopsied. Fortunately, most malignant laryngeal lesions cause voice changes early in their course, so there is often little delay in diagnosis and treatment. The cure rates for early excisional surgery of small invasive lesions and laser therapy for carcinoma *in situ* are approximately 90% to 95%. Because micro- or minimally-invasive laryngeal carcinomas have such a high cure rate and so few surgical complications, once the voice has regained volume and intelligibility a return to flying is appropriate as long as regular follow-up visits are prescribed. Military policies vary; the U.S. Navy requires a 1-year grounding period after treatment of localized laryngeal cancers, but the U.S. Air Force does not specify a grounding period, only requiring that the patient be disease-free and fully recovered before a waiver can be considered.

Any neck mass is a cause for concern. Although most are benign and related to nearby inflammation or infection, they all deserve close scrutiny, as many head and neck malignancies first manifest as metastatic lymphadenopathy. Evaluation should start with an otolaryngology consultation, which will usually include upper aerodigestive endoscopy, CT or MRI, and a fine-needle aspiration biopsy (FNAB) of the mass. Incisional (partial) biopsy is rarely indicated because of the chance of causing local spread by breaching a malignant lesion. Total excisional biopsy has less chance of local seeding with malignant cells, and may be necessary if the nature of the mass remains uncertain. The removal of a proven benign mass, such as a thyroglossal duct cyst, is essentially elective if there are no troubling symptoms.

Lower midline masses are likely to be in the thyroid. Thyroid masses have a malignancy rate of approximately 20%, and an FNAB may not be helpful in making that distinction. Total lobectomy on the involved side is considered standard treatment when the diagnosis is uncertain. Further surgery might be necessary in the case of a malignancy. Radioactive iodine may be used to ablate residual gland tissue and make postoperative nuclear medicine imaging more sensitive in detecting residual thyroid tissue. Thyroid hormone replacement therapy carries little risk and is compatible with flying. Malignant diagnoses require regular monitoring for growth of residual tumor or metastases, but only the most aggressive malignancies, such as anaplastic and medullary carcinomas, have poor prognoses, with anaplastic being the most lethal as most patients succumb within a few months of diagnosis. Important complications of thyroid surgery are two: vocal cord paralysis and hypoparathyroidism. Vocal cord paralysis does not always cause a significant change in voice, but it does cause difficulty in raising volume, and the airway may be slightly compromised during exercise. If the voice is excessively breathy, thyroplastic surgery can help. Unilateral paralysis would likely have no effect on flying and should not be grounding if vocal communication remains good. Bilateral vocal cord paralysis can cause immediate dyspnea upon extubation, and needs urgent treatment. Even minimally symptomatic hypoparathyroidism may never improve and can be incompatible with flying.

Parathyroid adenomas rarely present as neck masses, and are only suspected when the serum calcium is elevated. Confirmatory testing reveals an elevated ionized calcium and inappropriately high parathormone (PTH) levels. Localizing an adenoma by noninvasive imaging, most commonly using a radioactive trace technique, can be difficult. Surgical options range from bilateral open neck explorations to minimally invasive techniques. If the adenoma is located and successfully removed, and PTH levels stabilize at normal levels, flying does not need to be restricted.

SUMMARY

The realm of otolaryngology encompasses a number of systems and organs that must be healthy before we can undertake or continue a flying career. For instance, when the inner ear is functioning normally, we are not at all aware of its presence, but if it should malfunction, it can produce immediate and incapacitating symptoms. The same applies to the middle ear and sinuses. When normal ventilation of these structures is compromised, pain can rapidly ensue, and if it is not totally incapacitating, it can surely distract the aviator from the task of flying. Awareness of the pathologic processes that affect the ENT area is vital to the practice of aerospace medicine.

ACKNOWLEDGMENT

The principal author of this chapter in the third edition, G. Richard Holt, MD, provided an excellent framework for the fourth edition chapter. He was unable to participate in the current edition in large part because of obligations to the U.S. Air Force Reserve, which included an extended tour in the Middle East. He has my heartfelt thanks for both his contributions and his service.

REFERENCES

1. Chen CY, Halpin C, Rauch SD. Oral steroid treatment of sudden sensorineural hearing loss: a ten year retrospective analysis. *Otol Neurotol* 2003;24:728–733.
2. Wilson WR, Byl FM, Laird N. The efficacy of steroids in the treatment of idiopathic sudden hearing loss. *Arch Otolaryngol* 1980;106:772–776.
3. Lieberthal AS, Ganiats TG, Cox EO, et al. American Academy of Pediatrics, American Academy of Family Physicians. Subcommittee on Management of Acute Otitis Media Clinical practice guideline. Diagnosis and management of acute otitis media. *Pediatrics* 2004;113:1451–1465.
4. Takata GS, Chan LS, Shekelle P, et al. Evidence assessment of management of acute otitis media: I. The role of antibiotics in treatment of uncomplicated acute otitis media. *Pediatrics* 2001;108:239–247.
5. Aggarwal R, Saeed SR, Green KJM. Myringoplasty. *J Laryngol Otol* 2006;120:429–432.
6. Dal T, Özlüoğlu LN, Ergin NT. The canalith repositioning maneuver in patients with benign positional vertigo. *Eur Arch Otorhinolaryngol* 2000;257:133–136.
7. Strupp M, Zingler VC, Arbusow V, et al. Methylprednisolone, valacyclovir, or the combination for vestibular neuritis. *N Engl J Med* 2004;351:354–361.
8. Tomooka LT, Murphy C, Davidson TM. Clinical study and literature review of nasal irrigation. *Laryngoscope* 2000;111:1867–1869.
9. Benninger MS. Therapeutic choices in the treatment of acute community-acquired bacterial rhinosinusitis. *Am J Rhinol* 2006;20: 662–666.
10. Scully C. Aphthous ulceration. *N Engl J Med* 2006;355:165–172.
11. Brandfonbrener A, Epstein A, Wu S, et al. Corticosteroid therapy in Epstein-Barr virus infection. Effect on lymphocyte class, subset, and response to early antigen. *Arch Intern Med* 1986;146:337–339.
12. Candy B, Hotopf M. Steroids for symptom control in infectious mononucleosis. *Cochrane Database Syst Rev* 2006;3:CD004402.
13. Tynell E, Aurelius E, Brandell A, et al. Acyclovir and prednisolone treatment of acute infectious mononucleosis: a multicenter, double-blind, placebo-controlled study. *J Infect Dis* 1966;174:324–331.
14. DeVault KR, Castell DO. Updated guidelines for the diagnosis and treatment of gastroesophageal reflux disease. *Am J Gastroenterol* 2005;100:190–200.

RECOMMENDED READINGS

Bailey BJ, Johnson JT, Newlands SD, eds. *Head and neck surgery–otolaryngology*, 4th ed. Philadelphia: Lippincott Williams & Wilkins, 2006.

Brook I. *Sinusitis*. New York: Taylor & Francis, 2006.

Cummings CW, Haughey BH, Thomas JR, et al., eds. *Cummings otolaryngology*, 4th ed. Philadelphia: Elsevier Science, Mosby, 2005.

Jahn AF, Santos-Sacchi J. *Physiology of the ear*. New Haven: Singular, 2001.

Lee KJ. *Essential otolaryngology*, 8th ed. New York: McGraw-Hill, 2002.

Sataloff RT, Sataloff J. *Hearing loss*, 4th ed. New York: Taylor & Francis, 2005.

Snow JB, Ballenger JJ, eds. *Ballenger's otorhinolaryngology: head and neck surgery*, 16th ed. Lewiston: BC Decker, 2003.

Additional Reference Material

The American Society of Aerospace Medicine Specialists has made its Aerospace Medicine Practice Guidelines available at: http://www/asams.org/guidelines.htm Pertinent to this chapter are the guidelines for Acoustic Neuroma, Allergic Rhinitis, Cholesteatoma, Gastroesophageal Reflux Disease, Ménière's Disease, Sinusitis, and Sleep Disorders. Other sources of information are the US Navy Aeromedical Reference and Waiver Guide (http://www.nomi.med.navy.mil/NAMI/WaiverGuideTopics/index.htm), the US Air Force Waiver Guide (www.airforcemedicine.afms.mil/waiverguide), and the US Army's Aeromedical Policy Letters. https://aamaweb.usaama.rucker.amedd.army.mil/AAMAWeb/policyltrs/Army_APL

CHAPTER 16

Aerospace Neurology

John D. Hastings

Listen to your patients. Listen and they will tell you what's wrong with them. And if you listen long enough, they will even tell you what will make them well.

—*Walter C. Alvarez*

A doctor who cannot take a good history and a patient who cannot give one are in danger of giving and receiving bad treatment.

—*Author Unknown*

The greatest mistake in the treatment of diseases is that there are physicians for the body and physicians for the soul, although the two cannot be separated.

—*Plato*

In the practice of medicine, the neurologist is called upon to answer the following questions (1):

1. Does the patient have neurologic disease?
2. If so, what is the localization of the lesion or lesions?
3. What is the pathophysiology of the process?
4. What is the preliminary differential diagnosis?

Utilizing the tools of the neurologic and medical history, the neurologic examination, ancillary studies, and one's education, training, and experience the neurologist arrives at a diagnosis. The aerospace medicine physician (evaluator) has the additional challenge of relating the neurologic condition to aviation safety and achieving an appropriate aeromedical disposition. Whether it is aviation medical examiner, flight surgeon, or regulator, the aerospace medicine physician shoulders the responsibility of a determination that may decide one's career in aviation or space. Considering the individual, and yet preserving aviation safety, is a never-ending challenge for the aerospace medicine physician. The evaluator has the dual responsibility of applying the standards, and also considering exceptions to the standards in allowing waivers from standards, while assuring aviation safety.

An important consideration in aeromedical disposition is the nature of the operation or the mission, as a condition might not be compromising in all aerospace operations. The evaluator must consider the condition in relation to space operations, potentially of long duration, military versus civil operations, single versus multicrew operations, and the nature of the operation. Demands within civil, private, commercial, and airline transport operations must be considered. For example, a history of migraine with certain characteristics might potentially compromise military operations where immediate worldwide deployment is possible, but the condition might be considered an acceptable risk for multicrew or private pilot operations.

PRINCIPLES OF AEROSPACE NEUROLOGY

When a neurologic condition exists, the evaluator should consider the following:

1. Is the condition static? If so, what is the degree of functional incapacitation?
2. Is the condition progressive? If so, is the course predictable or unpredictable?
3. Can the condition be monitored successfully?
4. Can the condition result in sudden incapacitation?
5. Can the condition result in subtle incapacitation?

A pitfall in aeromedical disposition of aviators with neurologic disorders is making a major decision based on limited information. In neurologic diagnosis, the history is most often the richest source of information. The neurologic examination is often normal. Ancillary studies including laboratory studies, neuroimaging procedures, and sometimes sophisticated studies such as cardiac electrophysiological studies may also be normal. Often, the history is the sole means of diagnosis. One need only consider the migraineur, the epileptic with a normal electroencephalogram (EEG), the person with a transient ischemic attack (TIA) and no vascular bruit, or the victim of transient global amnesia (TGA) to grasp the importance of history.

The aerospace medicine physician is somewhat disadvantaged because evaluation is based on obtained medical records and history taken by others. Most often, the evaluator has no opportunity to interact with the individual or obtain one's own history. Yet efforts to obtain additional information when the history is inadequate often bear the most fruit. Observations of emergency services personnel, description of an event by a spouse or other observer, or comments from fellow aircrew may hold the key to diagnosis and appropriate aeromedical disposition. Diligent pursuit of a complete history is the evaluator's best guide to aeromedical disposition.

Another important consideration in neurologic diagnosis is the role of psychological factors. Symptoms that reflect true neurologic illnesses are often intertwined with complaints that have an emotional basis, and teasing out the respective contributions is important for the evaluator. Moreover, psychological influences often play an important role in a number of common disorders encountered by the neurologist. The influence of emotions in migraine, syncope, and chronic daily headache exemplifies this relationship.

This chapter does not address individuals in whom neurologic disease is absent. Rather, it addresses those who suffer from a neurologic condition, which may or may not compromise aviation safety, resulting in temporary or permanent disqualification or operational limitations.

The following pages will attempt to apply these principles to specific neurologic conditions encountered in aerospace medical certification.

EPISODIC DISORDERS

Episodic neurologic disorders, including migraine, cluster headache, TGA, syncope, epilepsy, the single seizure, and vertigo, are of aeromedical significance because of the potential for sudden incapacitation. Some merit permanent disqualification, whereas others may be accommodated with treatment or operational limitations. Vertigo will be dealt with in Chapter 15. Although "central" vertigo may occur in association with brain stem disease [e.g., multiple sclerosis (MS) or ischemic vascular disease], most cases of paroxysmal vertigo represent peripheral vestibulopathies.

Migraine

Migraine is common, with a prevalence of 17% in women and 6% in men. Common features of migraine include unilaterality (exclusively or predominantly one-sided), throbbing nature, nausea, vomiting, photophobia, phonophobia, and prostration. The migraine sufferer commonly prefers a dark, quiet room and relief may follow sleep. The headache may last hours to days and is commonly followed by a drained feeling and remnants of pain with head movement. Although migraine may be spontaneous, there are many precipitants including sleep deprivation, hunger, sun exposure, fatigue, menses or oral contraceptives, foodstuffs, alcohol, and emotional stress. Migraineurs tend to have perfectionistic and orderly personality traits, and family history is positive in 60% of cases. Migraine can appear at any age but commonly in adolescence, sometimes entering remission and appearing years later.

In common migraine, the headache begins without an antecedent aura. In classic migraine, an aura precedes the headache by 15 to 30 minutes. Visual auras are common with myriad descriptions including scintillating or sparkling lights, visual field defects such as hemianopia, colored or kaleidoscopic whorls or patterns, or patterns such as zigzag lightning or herringbone patterns. An important diagnostic feature is the "positive" nature of the visual aura, meaning the presence rather than the absence of light (ischemia characteristically is a "negative" visual phenomenon with absence of light). Nonvisual auras also occur, with symptoms such as marching face and hand numbness, or expressive speech difficulty.

A third variety of migraine is "migraine equivalent" (migraine variant, acephalgic migraine), in which a migraine aura occurs without developing a headache. Visual migraine equivalents are not uncommon beyond age 40(2), sometimes being mistaken for TIA due to cerebrovascular disease.

Rare forms of migraine include "complicated migraine," such as hemiplegic migraine accompanied by stroke, ophthalmoplegic migraine with oculomotor nerve palsy, and basilar migraine with ataxia and confusion.

Migraine may or may not be of aeromedical significance depending on its characteristics in a specific individual, and operational considerations (e.g., potential global military deployment versus private pilot operations). To guide aeromedical disposition, the evaluator should consider a host of factors, including the following:

1. ***Prodrome***: Some migraine sufferers will experience a prodrome of hours to a day or more, characterized by a sense of uneasiness, anxiety, apprehension, or general feeling of ill being. Recognition of prodrome may allow the aviator to avoid flying.
2. ***Precipitating factors***: Many migraineurs will report specific precipitating factors, which, if avoided, may reduce migraine risk or preclude migraine altogether. These include emotional stress, multitask overload, sleep deprivation, fasting, foodstuffs and certain alcohols, menses, and other precipitants.
3. ***Migraine aura***: Is the aura minor, or is there significant functional impairment? For example, slight perioral and unilateral fingertip paresthesiae may be inconsequential, as would a sliver of shimmery light in the far periphery of the visual field. Alternatively, a complete homonymous hemianopia or prominent aphasia would significantly compromise the individual.
4. ***Rapidity of onset***: Some migraines develop rapidly, with vomiting and prostration occurring within 15 to 30 minutes of onset. Others develop slowly, perhaps beginning as an annoying discomfort over one eye, but not developing into a severe headache for hours. Onset during flight would allow corrective measures in this circumstance.
5. ***Frequency***: Migraine-free intervals can vary widely from days to years or even decades. An individual experiencing several migraines per month would cause concern; a frequency of two per year would be far less worrisome.
6. ***Acute treatment measures***: Aspirin, nonsteroidal anti-inflammatory drugs (NSAIDs), and acetaminophen may be effective if taken early. These would be acceptable in an aviation environment. Triptans may be acceptable with timing limitations in relation to flight. Anticonvulsants, narcotic analgesics, and barbiturate-containing analgesics would be prohibitive.
7. ***Preventive treatment***: Medications employed in migraine prophylaxis include β-blockers, calcium channel blockers, anticonvulsants, and antidepressants including tricyclic and selective serotonin reuptake inhibiting agents. β-Blockers and calcium channel blockers may be acceptable in aviation, whereas the others are prohibitive due to potential central nervous system effects.

Considering the prevalence of migraine, the diagnosis need not be disqualifying in most individuals. Individual consideration with attention to the features enumerated earlier may allow favorable aeromedical disposition depending on the aviation environment.

Cluster Headache

True cluster headache, formerly known as *histamine headache* or *Horton's headache,* has very distinct clinical characteristics. The term *cluster* refers to a series of headaches lasting from weeks to months separated by symptom-free intervals of many months to several years or more. Each headache is identical for that individual. Clinical characteristics may include abrupt onset with intense pain peaking within a minute or two, unilateral location in or behind one eye, unilateral nasal stuffiness, drainage, eye redness, tearing, and perhaps a Horner syndrome (ptosis and pupillary constriction). Excruciating pain persists for 30 to 45 minutes followed by rapid resolution of symptoms. Headaches may occur precisely at the same time each day. After one or more headaches daily for a period, the cluster ends, affording welcome relief.

Cluster headache is treated with narcotic analgesics and other analgesics, lithium carbonate, and at times oxygen (a potent vasoconstrictor). Severe pain and analgesic requirements during a cluster are disqualifying, but long periods of remission usually allow certification once the cluster ends.

Other Headache

Although not included in the episodic disorders, the most commonly occurring headache is chronic daily headache, formerly referred to as *tension headache*. This is a frequent (daily or nearly so) headache, often dull to moderate, nagging but not incapacitating, with resistance to treatment. It may be a component of a somatoform disorder, and in one study 46% of individuals with a primary complaint of chronic headache suffered from endogenous depression (3). The underlying condition and therapeutic agents utilized (narcotic- or barbiturate-containing analgesics, antidepressants, tranquilizers) ordinarily preclude aeromedical certification unless underlying issues are resolved.

Transient Global Amnesia

TGA is a fascinating condition whose prime characteristic is severe anterograde and extensive retrograde amnesia. Initially described in 1954, TGA is a global amnesic state that resolves within 24 hours. Personal identity, level of consciousness, awareness, and ability to perform complex acts are well preserved, distinguishing TGA from confusional states. Strict diagnostic criteria include presence of a capable witness, clear anterograde amnesia, alert wakefulness, normal content of consciousness beyond memory, absence of focal symptoms and a normal neurologic examination, and resolution within 24 hours.

Although TGA has been reported from age 5 to 92 years, 90% of cases occur in the 50 to 80 range. Most attacks are 4 to 6 hours in duration, with retrograde amnesia ranging from hours to months and sometimes years, which upon recovery shrinks to a permanent retrograde gap of 1 hour.

Precipitating circumstances reported in TGA include cold water immersion, sexual intercourse, painful experiences, and medical procedures such as angiography on rare occasions. Association with physical exertion is present in 18%, emotional stress in 14% to 44%, and with migraine in 25% to 33% of cases.

At the onset of TGA there is disorientation for time and place, but preservation of personal identity. Repetitive asking of questions is a near universal feature. Preserved ability to perform complex acts such as operating an aircraft or performing detailed carpenter work is a constant feature of TGA. Migraine-like headaches are associated with TGA in approximately 50% of patients.

Unilateral or bilateral medial temporal hypoperfusion has been demonstrated during TGA with magnetic resonance imaging (MRI) techniques, and experimentally, a slowly spreading cortical depression across the cerebral cortex has been shown. Interestingly, a similar mechanism of cortical spreading depression has been postulated in the aura of migraine.

Most individuals with TGA suffer a single episode, although recurrence rates of 3% annually over 5 years have been reported. Aeromedical disposition often depends on specific precipitating factors and often a period of symptom-free observation.

A monograph by Hodges (4) provides a comprehensive review and discussion of TGA.

Syncope

The importance of history in neurologic diagnosis is clearly apparent when dealing with disorders of consciousness. Differentiating syncope from seizure (faint from fit) is a never-ending challenge for the aeromedical physician. An erroneous diagnosis has profound implications for the aviator. Up to one third of persons suffering syncope with convulsive accompaniments are incorrectly given a diagnosis of epilepsy.

The essence of syncope is loss of consciousness and postural tone due to global cerebral hypoperfusion followed by spontaneous recovery. In near syncope (presyncope), the process is incomplete (perhaps by a compensatory action such as sitting down), with partial preservation of consciousness.

Syncope is common, with a reported occurrence of 3+% in the Framingham Study. Approximately 75% of these individuals reported a single occurrence with a mean follow-up of 26 years. In a study of 3,000 healthy United States Air Force (USAF) personnel averaging 29 years of age, 2.7% reported syncope (5).

In the 1942 text *Fit to Fly, A Medical Handbook for Fliers,* coauthored by Grow and Armstrong, the following text appears: "Low blood pressure occurs in 2.5% to 5% of the population and is probably more common in hot climates. Usually it indicates a person who is under par physically. They are usually underweight, show narrow, flat chests with poor expansion, and they commonly complain of lassitude, giddiness, vertigo, and a tendency to faint" (6). There are no other references to syncope in the text.

Syncope occurs due to impaired homeostasis, the normal state of appropriate balance and regulation of cardiac output, circulating blood volume, and peripheral resistance provided by peripheral arterial smooth muscle. When one stands, 70% of circulating blood volume lies at or below the heart. Gravity pools 500 to 800 mL of blood in dependent vascular spaces in the lower extremities, with concomitant reduction in central venous pressure by 3 to 5 mm Hg and stroke volume by 50%. Resultant diminished baroreceptor stimulation leads to compensatory mechanisms including enhanced sympathetic and inhibited parasympathetic activity. Heart rate increases 10 to 25 beats per minute and sympathetic efferents to arterioles command an increase in peripheral resistance. Mean arterial blood pressure is preserved, assuring maintenance of homeostasis. Sudden pain, fear, and a host of other precipitants can momentarily defeat the delicate balance of homeostatic mechanisms, and syncope occurs.

The term *vasovagal syncope,* coined by Lewis in 1932, refers to dual mechanism of loss of peripheral vasoconstriction (collapse of peripheral resistance) and cardioinhibition (vagus-induced bradycardia). Terms appearing in contemporary literature including neurally mediated, neuroregulatory, and neurocardiogenic syncope are synonymous. Lewis recognized that loss of peripheral resistance was the predominant mechanism in most instances of syncope. The term *vasodepressor syncope* denotes hypotension without significant bradycardia, whereas *cardioinhibitory syncope* refers to vagally induced bradycardia as the predominant mechanism. This is a clinically important distinction.

The cardioinhibitory reflex can be powerful. Ventricular standstill and fibrillation have been reported with psychological stimuli. In contrast to vasodepressor syncope, cardiac syncope is sudden in onset. With asystole, presyncope occurs within several seconds and loss of consciousness within 6 to 8 seconds when upright. Injury and sudden death are attendant risks in malignant forms of cardioinhibitory syncope.

When evaluating syncope, the evaluator must ask first "Is it syncope or something else?" The following historical points aid accurate diagnosis:

1. ***Postural setting***: Syncope characteristically occurs when upright, less often while seated, and rarely in recumbency. Seizures do not respect posture.
2. ***Length of prodrome***: In vasodepressor (noncardiac) syncope, there is usually a lengthy prodrome of 2 to 5 minutes. Feelings of uneasiness, warmth, anxiety, and queasiness are common during the prodrome, along with a desire for cool air and ventilation. In contrast, seizure auras, if present, are usually brief.
3. ***Antecedent symptoms***: Visual complaints including pale, yellow, white, bleached, darkened, or constricted vision ("tunnel vision") denote retinal ischemia, indicating an extracerebral mechanism for the event. Respiratory antecedents might include yawning or deep breathing. Gastrointestinal (GI) symptoms include an empty, hollow, or unsettled sensation in the epigastrium. Anxiety, dry mouth, and clamminess in the forehead and hands are common. Giddiness and lightheadedness may occur as the systolic blood pressure approaches 70 mm Hg, but, unlike true vertigo, there is no element of rotation of the environment or the body.
4. ***Syncopal episode***: Syncope is a brief event, lasting 10 to 15 seconds, with little or no confusion. It is a hypotonic rather than rigid event ("syncopal slump") with pallor (white—loss of color, rather than blue). Respirations are shallow and often imperceptible. Return of consciousness is rapid, as is alertness. The embarrassed victim may

rise quickly only to repeat the episode. This feature is diagnostic of vasovagal syncope.

5. ***Convulsive accompaniments and urinary incontinence***: In experimental syncope, the EEG background frequency slows, lowers in amplitude, and eventually becomes flat, devoid of activity, as syncope ensues. In 10% to 15% of fainters, brief myoclonic jerks of the face and hands, tonic posturing, or other brief seizure-like activity occurs. This phenomenon constitutes the *convulsive accompaniment* that may occur in syncope. This is *not* a seizure, which is characterized by excessive neuronal discharges rather than absence of cortical activity. This convulsive accompaniment rather reflects a state of functional decerebration. In addition, approximately 10% of fainters experience urinary incontinence, which, if coupled with convulsive accompaniments, may lead to an erroneous diagnosis of seizure or epilepsy in one third of cases.
6. ***The syncopal setting***: The situation or the circumstances in which the event occurs is of utmost importance. Worry, emotional upset, medication, alcohol, physical exertion, dehydration, medical procedure, or other precipitants may be present.

The evaluator, having determined that syncope has indeed occurred, must attempt to determine the cause or mechanism if possible. Table 16-1 lists potential causes of syncope.

Fortunately 50% or more of syncope is benign and does not signify underlying disease. A careful history and physical examination may indicate the cause of syncope in 25% to 35% of fainters and in 75% of persons in whom a cause is found (7). Basic laboratory tests (complete blood count, chemistry panel) and 12-lead electrocardiogram (ECG) may provide an answer in 5% to 10% of patients. Further studies should be guided by the history and physical findings, and may direct one toward cardiac studies such as echocardiogram, Holter monitor, ambulatory event recording, or ultimately electrophysiological studies. Brain MRI and EEG studies are usually not helpful.

When initial studies do not provide an explanation, head-up tilt (HUT) table testing may be helpful in the evaluation of syncope. HUT may be positive in 50% of cases of syncope of unknown cause, supporting a vasovagal mechanism for the event. However, HUT without pharmacologic activation has a false-positive rate of approximately 10%, rising to 27% or more with pharmacologic activation (commonly nitroglycerine). False-positive studies have led to an incorrect diagnosis of syncope in individuals with clinical seizures. Other caveats involving HUT include nonstandard tilt angles, variable tilt duration, and lack of reproducibility in some studies. HUT is not recommended in the routine evaluation of syncope.

Aeromedical disposition in syncope can be favorable in most instances in which a benign mechanism, that is not likely to recur in flight, can be demonstrated. Satisfactory exclusion of serious causes of syncope can be accomplished with appropriate testing, and a period of symptom-free observation might provide further assurance.

TABLE 16-1

Etiology of Syncope

- Reflex-mediated vasomotor instability
  - Vasovagal (neurocardiogenic, neurally mediated, neuroregulatory) syncope: the common faint
  - Situational syncope (related to a particular circumstance)
    - Cough (tussive) syncope
    - Sneeze
    - Swallow
    - Defecation
    - Postmicturition syncope
    - Weight lifting
    - Exercise induced
    - Trumpet player
    - Mess trick
    - Valsalva
    - Medical procedure: physical examination (eye-oculovagal, ear, etc.), venipuncture, genitourinary or gastrointestinal instrumentation, etc.
    - Hot tub or shower
  - Orthostatic/dysautonomic
    - Primary autonomic dysfunction (autonomic neuropathy, CNS disorders)
  - Secondary autonomic dysfunction
    - Medications, alcohol
    - Prolonged illness, prolonged bedrest
    - Hypovolemia (blood loss, dehydration)
  - Impaired cardiac output
    - Obstructive disease: aortic stenosis, idiopathic hypertrophic subaortic stenosis, pulmonary stenosis
    - Pump failure: myocardial infarction, coronary artery disease, cardiomyopathy
  - Impaired cardiac rhythm
    - Bradycardias
    - Tachycardias
    - Mixed rhythm disturbances: sick sinus (brady/tachy) syndrome
  - Psychiatric disease
  - Miscellaneous
    - Carotid sinus syncope
    - Glossopharyngeal neuralgia
    - Anemia
- Unknown

Adapted from Benditt DG, Lurie KG, Adler SW, et al. Pathophysiology of vasovagal syncope, Table 1, 3; and Kapoor WN. Importance of neurocardiogenic causes in the etiology of syncope. Table 1, 56. In: Blann JJ, Benditt D, Sutton S, eds. *Neurally mediated syncope: pathophysiology, investigations and treatment*. The Bakken Research Center Series, Vol. 10. Armonk, NY: Futura, 1996; with permission. CNS, central nervous system.

Seizure Disorder

Seizure disorder, convulsive disorder, and epilepsy are synonymous terms. A seizure is an abnormal, paroxysmal excessive discharge of cerebral neurons. Epilepsy is a chronic condition characterized by a tendency for recurrent (two or more), unprovoked seizures. The cumulative incidence of epilepsy is between 1.3% and 3.1% by age 80, with high incidence peaks in those younger than 20 and older than 60 (11). Epilepsy is idiopathic in two thirds of patients.

Not all seizures represent epilepsy. All persons have a constitutional or genetically determined threshold for seizures, which if exceeded, leads to a clinical event. This threshold may fluctuate with time of day, hormonal influences, sleep deprivation, and other factors. *Acute symptomatic* seizures may occur with electrolyte disturbances (e.g., severe hypoglycemia or hyponatremia), infectious processes (e.g., pneumococcal meningitis with high-dose penicillin), and cardiac arrest with prolonged asystole and ensuing cerebral ischemia. Individuals with low-seizure threshold may experience seizures when exposed to medications (tricyclic antidepressants, bupropion, theophylline, and other medications). Additionally, some individuals with established epilepsy may achieve permanent remission (e.g., benign childhood epilepsy with centrotemporal spikes).

For aeromedical purposes, a simple classification for seizures is adequate; it is presented in Table 16-2. Seizures are generalized from the onset in approximately half the cases and of partial onset in the remainder. Whereas generalized seizures are accompanied by simultaneous appearance of abnormal discharges throughout the cerebral cortex at onset, as the name implies, partial seizures (focal seizures in older terminology) arise in a discrete area of the cerebral cortex. This is significant in that a partial seizure implies a focal lesion, which must be identified (scar, tumor, abscess, cavernous angioma, other).

In simple partial seizures, consciousness is preserved. Localized convulsive twitching of one hand might be caused from a lesion in the contralateral cerebral cortex. The individual remains alert, can carry on activity, and ordinarily suffers no after effects with cessation of the seizure.

In complex partial seizures, consciousness is impaired or even lost. Complex partial seizures are commonly preceded by an aura of myriad descriptions. *Déjà vu* experiences, an unpleasant smell (olfactory aura) or taste (gustatory aura), a forced thought, vivid visual memory, or feeling of detachment from one's self, may precede the seizure. The victim may engage in stereotyped movements such as repetitive lip-smacking, chewing movements, or hand or body movements such as fumbling with an object or rubbing a table. Awareness of surroundings is either compromised or lost, and one may or may not lose consciousness.

TABLE 16-2

Basic Classification of Seizures

1. Seizures that are generalized from the onset (e.g., idiopathic grand mal epilepsy, classic petit mal epilepsy)
2. Simple partial seizures with preservation of consciousness (e.g., focal motor seizure)
3. Complex partial seizures with alteration of consciousness (e.g., psychomotor seizure, temporal lobe automatism)
4. Partial seizures with secondary generalization (focal onset, progressing to generalized tonic-clonic seizure)

Any partial seizure may spread to adjacent areas of cortex and eventually to deep-seated midline structures that project to all areas of the cerebral cortex, culminating in a generalized tonic-clonic (grand mal) seizure. For example, a focal seizure beginning in one hand as described earlier may spread to the forearm, upper arm, face, and leg (jacksonian march described by Hughlings Jackson), followed by collapse and a grand mal seizure. This is a partial seizure with secondary generalization.

A generalized tonic-clonic seizure is announced by a tonic phase lasting 10 to 20 seconds, with brief flexion, then muscular rigidity with arms raised, abducted, partially flexed at the elbows, and externally rotated. Leg involvement is minor. Eyes remain open with upward deviation of the globes. Extension of the back and neck then follows, perhaps accompanied by an "epileptic cry" resulting from forced expiration through partially closed vocal cords. Arms and legs are extended, with apnea and cyanosis. The clonic phase then begins, which is in reality a rhythmic relaxation of tonic contractions. Clonic jerks become coarser and decline in frequency as relaxation phases lengthen. Tongue biting and urinary incontinence are common.

Grand mal seizures are characteristically followed by a postictal state, which often includes a deep, snoring sleep. Return of consciousness follows with a confused and often combative arousal phase, which gradually clears. Nausea, vomiting, and headaches are common. Violent muscular contractions leave the trunk and extremity muscles sore and tender, and shoulder dislocations or vertebral compression fractures may occur. The victim wants to sleep, and upon returning to wakefulness is amnesic for the event.

Petit mal (absence) seizures represent another variety of generalized epilepsy. Frequently appearing in childhood, petit mal seizures are characterized by brief lapse of awareness that may or may not be accompanied by myoclonic jerks and alterations of muscle tone. Brief loss of awareness, with repetitive eye flutter for 2 to 3 seconds, would be a representative example. The individual immediately resumes normal activity, and, if the spell is brief, may remain unaware of its occurrence.

As with syncope, a careful history is of utmost importance in the evaluation of one or more seizures. Description by an observer might be the most important ingredient in accurate diagnosis. Records from paramedics and ambulance personnel, and detailed emergency room records including physician evaluations and nursing notes, may provide important details in accurately defining the clinical event. Personal history, family history, medication, and social history including alcohol and substance misuse are clearly important.

Seizure evaluation, particularly in adults, must include brain MRI with and without gadolinium and a sleep-deprived wake and sleep EEG. Computed tomography (CT), even with contrast is insufficient because lesions such as mesial temporal sclerosis, hamartoma, or cavernous malformation might be overlooked. Wake-only EEG recordings are not sufficient because activation of a potentially epileptiform discharge might occur only during sleep recording. Photic stimulation is employed to elicit reflex-induced seizures (photic epilepsy) in susceptible individuals. It is important to note that up to 40% of individuals with epilepsy have normal EEGs throughout their lives, again emphasizing the importance of history.

Clearly, a detailed evaluation is needed in the aeromedical disposition of persons with seizures or a question of seizures. A history of febrile seizures does not imply chronic seizure potential. Some persons with seizures achieve complete remission in adulthood, such as benign Rolandic epilepsy with centrotemporal spikes. Individuals with acute symptomatic seizures do not harbor chronic seizure potential. A thorough neurologic evaluation, at times coupled with a period of seizure-free and medication-free observation, may allow medical certification.

The Single Seizure

A single unprovoked seizure does not constitute epilepsy unless it is followed by a second unprovoked event. An individual suffering a first-ever seizure should undergo a comprehensive general medical and neurologic evaluation.

Degree of recurrence risk following a single unprovoked seizure can be related to risk factors. A history of febrile seizures or seizure occurrence in a first-degree relative elevates the risk, as does a history of remote neurologic insult or previous acute symptomatic seizure. An abnormal neurologic examination or abnormal imaging study is associated with increased risk of recurrence. EEG abnormalities are also important. Specifically, epileptiform abnormalities are associated with a 60+% risk of recurrence, nonspecific slowing with a 30% to 40% risk, and with a normal EEG 10% to 25% risk (12,13).

Absent risk factors, recurrence risk is in the 26% to 33% range over 5 years (12), after which recurrence risk approximates that of the normal population. Most epileptologists elect not to treat individuals with a first-ever seizure and no risk factors because the majority would be treated unnecessarily. This is important for the aviator because a 5-year period of seizure-free and medication-free observation might allow consideration for aeromedical recertification.

Initial treatment with anticonvulsants delays the process. A second seizure during that period satisfies the criteria for epilepsy (two or more unprovoked seizures), and recurrence risk following a second seizure escalates to 73%.

CEREBROVASCULAR DISEASE

Stroke is the third leading cause of death in the United States and a major contributor to disability. Approximately 700,000 strokes occur in the United States annually, of which 200,000 are recurrent strokes. Approximately 85% of strokes are ischemic, whereas the remaining are hemorrhagic.

Ischemic Stroke

Ischemic stroke may be classified based on the presumed nature of focal brain injury and the type and localization of the vascular lesion (11). Major categories include large artery atherothrombotic infarction (extracranial, intracranial, or cardioembolic), small vessel disease, other causes (dissection, hypercoaguable states), and stroke of indeterminate cause.

Approximately 20% to 30% of strokes are cardioembolic. Large vessel disease is responsible in 15% to 20% of cases, 75% of which is extracranial in origin (carotid or vertebral arteries, aorta), the remainder arising from intracranial large vessels (intracranial portions of major arteries, basilar, anterior, middle, and posterior cerebral arteries and major branches). Small vessel disease (lacunar stroke) comprises approximately 20% stroke cases (12). Coagulation disorders account for 1% to 5% of cases of stroke, and stroke without demonstrable cause (cryptogenic stroke) occurs in a significant proportion of stroke victims.

The aeromedical physician must address the issue of stroke in terms of primary prevention, secondary prevention, assessment of degree of significant functional disability, and determination of recurrence risk.

Nonmodifiable risk factors for stroke include age (risk doubles in each decade for those older than 55 years), gender (males have higher risk than females), race (African Americans and Hispanics have higher risks than whites), and genetics (family history may increase risk).

Well-documented modifiable risk factors for stroke include prior TIA/stroke, hypertension, diabetes, tobacco use, dyslipidemia, cardiac disease, atrial fibrillation, and asymptomatic carotid stenosis. Additional factors not fully supported by rigorous science include alcohol and drug abuse, physical inactivity, impaired nutrition, hypercoaguable states, elevated homocysteine, hormone replacement therapy, and oral contraceptives.

Primary prevention of stroke involves vigorous attention to modifiable risk factors, which includes treatment of hypertension, physical exercise, addressing dyslipidemia with diet and/or medication, smoking cessation, avoiding excess alcohol ingestion, and detection and treatment of cardiac disease and significant asymptomatic carotid artery stenosis. Stringent diabetes management is important if the disease is present.

Secondary prevention following ischemic stroke involves identification and mitigation of modifiable risk factors (13). Hypertension contributes to a variety of ischemic stroke subtypes through atherosclerosis, small vessel lipohyalinosis, and cardiac impairment. Effective management of hypertension alone can reduce stroke incidence by as much as 70% (14). In the PROGRESS trial, a combination of perindopril and indapamide produced a 43% reduction in recurrent stroke risk without regard to initial blood pressure (15). The seventh report of the Joint National Committee on Prevention, *Detection, Evaluation, and Treatment of High Blood Pressure* (JNC-7) classifies blood pressure of less than 120/less than 80 as normal, 120–139/80–89 as prehypertension, 140–159/90–99 as hypertension stage I, and 160/100 or greater as hypertension stage 2 (16). Lifestyle modifications including weight control, physical activity, and moderation of sodium intake are recommended for persons with prehypertension. Along with lifestyle modifications, guidelines recommend thiazide-type diuretics, perhaps combined with a single agent for stage I hypertension, and for stage II hypertension two-drug combination for most (thiazide-type diuretic along with an angiotensin-converting enzyme inhibitor, angiotensin receptor blocker, β-blocker, or calcium channel blocker).

Hyperlipidemia elevates stroke risk, particularly carotid artery–related strokes (17). American Stroke Association (ASA) guidelines recommend adopting National Cholesterol Education Program guidelines, which advise lifestyle modification, dietary changes, and medication for TIA or stroke patients with elevated cholesterol, comorbid cardiac disease, or evidence of atherosclerotic origin.

Diabetes is a clear risk factor for stroke, being present in 15% to 33% of ischemic stroke victims. Additionally, smoking is a highly significant independent risk factor for ischemic stroke. It is generally accepted that heavy alcohol consumption elevates stroke risk in all subtypes, with perhaps a protective effect in light to moderate drinkers, such as 1 to 2 ounces daily. Less well-documented evidence exists for obesity and physical inactivity.

ASA guidelines advocate carotid endarterectomy for symptomatic (TIA or stroke) patients with severe carotid stenosis (70%–99%), and in selected patients with 50% to 69% stenosis. Asymptomatic carotid stenosis is receiving increased attention along with treatment options. In unselected populations, 7% of men and 5% of women older than 65 years have greater than 50% carotid artery stenosis. The risk of stroke with greater than 60% stenosis is approximately 2% per year, with a myocardial infarction risk of approximately 5% per year (18). Treatment of asymptomatic carotid stenosis is controversial. Dodick et al. recommend consideration of carotid endarterectomy in patients with asymptomatic carotid artery stenosis only for medically stable patients with stenosis of 80% or greater who are expected to live for 5 years, and then only with surgeons who have a perioperative complication rate of less than 3% (19). Evidence-based guidelines for clinicians put forth by the American Academy of Neurology support these parameters for patients aged between 40 and 75 with 60% to 99% stenosis.

Atrial fibrillation is associated with significant risk of cardioembolic stroke. Trials have shown a relative risk reduction of 68% and an absolute reduction in annual stroke rate from 4.5% to 1.4% in patients treated with dose-adjusted warfarin.

Along with primary and secondary prevention strategies and assessment of residual neurologic deficit for functional significance, the evaluator must address recurrence risk for aeromedical disposition.

In terms of overall risk, up to 30% of persons suffering ischemic stroke will suffer recurrent stroke within 5 years (18). In the Northern Manhattan Stroke Study (NOMASS) involving a mixed ethnic cohort (40% black, 34% Hispanic, 26% white) older than age 39, stroke recurrence risk was 25% at 5 years (20). Survival was better with lacunar stroke. Dhamoon et al. reported an 18.3% risk of recurrent stroke over 5 years (mean age 69.7 and mean follow-up 4 years) (21). In the Perth Community Stroke Study reporting 10-year risk of first recurrent stroke, the recurrence risk was 43%, risk being highest within the first year and averaging 4% per year after the first year (22). Numbers were not large. Of 328 patients (69% with ischemic stroke), 30 persons suffered recurrent stroke in the first year, and 34 over the next 9 years. Predictors of recurrent stroke included increasing age, atrial fibrillation, high alcohol consumption, hemorrhagic stroke, and hypertension at the time of discharge. In a Spanish study (mean age 75.4 years), cumulative risk was 26% at 5 years, with age being the major predictor (23). In a British study, 5-year risk of recurrent stroke was 16.6% (24).

Recurrence risk varies with stroke subtype, an important consideration in aeromedical disposition. In a follow-up of at least 10 years of 178 patients with lacunar stroke, recurrent stroke occurred in 23.5% (annual risk of 2.4%) (25).

Stroke in the young warrants specific attention because recurrence risk may be lower compared to adults and etiology may vary. In a 5-year follow-up of 95 patients younger than 45 years, 4.7% suffered recurrent stroke (26). In the Baltimore-Washington Cooperative Young Stroke Study of 428 first strokes in persons aged 15 to 44, approximately 34.3% had stroke of indeterminate cause and another 18.7% had no probable cause but at least one possible cause (27). Identifiable causes included cardiac embolism (31.1%), hematologic/other causes (19.8%), nonatherosclerotic vasculopathy (11.3%), illicit drug use (9.4%), and migraine (1.4%). Large artery atherosclerotic disease accounted for only 3.8%. In a Spanish study of 272 young adults aged 15 to 45 with first-ever ischemic stroke, annual stroke recurrence rate was 3.6% during the first year, declining to 1.7% annually thereafter (28). In an Italian study of 60 patients aged 17 to 45 with TIA or ischemic stroke, recurrence rate was 7.4% over a mean span of 6.1 years (29).

Ischemic stroke of indeterminate cause (cryptogenic stroke) comprises a significant proportion of stroke (30%–40%) (30).

Medical information doubles within 10 years, and a MEDLINE search of cerebrovascular disorders from 1966 to 2004 generates more than 170,000 results (31). The evaluator seeking best evidence for aeromedical disposition in strokes must consider a large body of evidence outside his or her medical discipline. A principle of individual consideration utilizing best available evidence should be followed. Louis Caplan, Professor of Neurology at Harvard University who specializes in cerebrovascular disease, offered the following advice (personal communication, 2002):

> "My bias is and always has been that strokes are very heterogeneous and that the risk of recurrent strokes and seizures after stroke and cardiac risk varies with the etiology, nature, and location of the stroke in the individual. My advice would be to write no firm general rule, but to evaluate each individual case—preferably by a panel of individuals who specialize in stroke."

Hemorrhagic Stroke

Intracerebral hemorrhage (bleeding into brain parenchyma from an arterial source) is associated with hypertension in 72% to 81% of cases (32). Sites of bleeding include pons, cerebellum, basal ganglia, and lobar (subcortical white matter). Death or severe disability is common, ordinarily precluding return to flying.

Nonhypertensive causes of intracerebral hemorrhage include vascular malformations such as subdural hematomas or arteriovenous malformations, amphetamine use, cerebral amyloid angiopathy, vasculitis, and hemorrhage into metastatic tumor. Malignant melanoma is the third most common metastatic lesion to the brain following breast and lung, and hemorrhage is common.

Prognosis following intracerebral hemorrhage is not uniformly poor, and good recovery may be achieved with identification and idealization of risk factors or surgery. Judicious treatment of hypertension might reduce recurrence risk to an acceptable level. Complete resection of a vascular malformation may be curative following intracerebral hemorrhage, but seizure risk must be addressed. Although most malformations present with hemorrhage, a significant proportion (32%) are associated with seizures (33). Seizures tend to be associated with large malformations involving the cerebral cortex. Although complete surgical resection may eliminate risk of hemorrhage, risk of seizures arising from the surrounding neuronal bed might remain and preclude certification.

Intracranial Aneurysms

The most frequent cause of nontraumatic subarachnoid hemorrhage, accounting for 80% of cases, is a ruptured intracranial secular aneurysm (34). Prevalence of aneurysms greater than 3 mm in diameter has been reported in 4% of autopsies. Aneurysms commonly arise from major arteries at the base of the brain (circle of Willis) and are thought to arise from a combination of congenital defects in the muscular wall of the artery and degenerative changes injuring the internal elastic lamina. They involve the anterior circulation (anterior and middle cerebral artery distributions) in more than 80% of cases and are multiple in 31%. Mortality from ruptured aneurysms is 23%, and significant disability is present in more than 50% of survivors.

If an aneurysm is surgically isolated from the circulation and no others exist, the patient is cured. Conventional transfemoral cerebral angiography performed 3 to 12 months following surgery demonstrates cure. At times aneurysmal anatomy (e.g., fusiform or broad-necked aneurysm) precludes clipping, and noncurative procedures such as wrapping or use of glue are employed. Risk of bleeding, though perhaps lessened, remains.

The aeromedical evaluator's primary concern is residual neurologic impairment, which might include focal neurologic deficit or cognitive impairment. Careful neurologic evaluation is warranted, and an observation period of 1 year is commonly prescribed.

At times angiography does not demonstrate a source of bleeding despite multiple procedures. If an individual with idiopathic subarachnoid hemorrhage has no recurrence within 1 year, risk of further bleeding is acceptably low.

TRAUMATIC BRAIN INJURY

Traumatic brain injury (TBI) is a frequent cause of neurologic disability in the 20 to 55 age-group and is commonly encountered in aviators. The aeromedical evaluator is not concerned with acute management, but rather the possibility of persistent residual neurologic impairment. Essential ingredients in the evaluation of aviators with TBI include determination of the nature and severity of TBI.

Medical records will disclose the nature of TBI. Concussion is characterized by transient loss or alteration of consciousness (seconds to hours) caused by a blow to the head without evident tissue destruction. However, there may be microscopic injury, and petechial hemorrhage, axonal shearing with retraction bulbs, and edema may occur. Frank injury to brain parenchyma may occur through brain contusion, diffuse edema, laceration or penetration by a foreign object, and hemorrhage within the brain substance (intracerebral hematoma). Additionally, extraparenchymal bleeding (subdural or epidural hematoma) may cause cerebral injury through compression and herniation mechanisms.

Severity of TBI can be assessed utilizing the Glasgow Coma Scale (Table 16-3) and duration of posttraumatic amnesia (PTA) (Table 16-4). A Glasgow Coma score of 13 to 15

TABLE 16-3

Glasgow Coma Scale

Eye Opening	*E*	*Best Verbal Response*	*V*	*Best Motor Response*	*M*
Spontaneous	4	Oriented and converses	5	Obeys commands	6
To voice command	3	Confused	4	Localizes to pain	5
To pain stimuli	2	Inappropriate words	3	Withdraws from pain	4
No response	1	Incomprehensible sounds	2	Decorticate (flexion) posturing	3
		No sounds	1	Decerebrate (extension) posturing	2
				No response	1

$E + V + M = 3$ to 15.

TABLE 16-4

Posttraumatic Amnesia (PTA)

Mild brain injury	0–1 hr of PTA
Moderate brain injury	1–24 hr of PTA
Severe brain injury	1–7 d of PTA
Very severe brain injury	Beyond 7 d of PTA

denotes mild TBI, a score of 9 to 12 moderate TBI, and below 3 to 8 severe TBI by these criteria. When Glasgow Coma score and duration of PTA are coupled with records documenting the clinical course during the acute recovery period, the evaluator can accurately determine the severity of TBI. A Glasgow Coma score below 9 and/or PTA greater than 24 hours should heighten concern for persistent neurologic impairment.

Sequelae of TBI include postconcussion syndrome, focal neurologic deficit, neuropsychological residual, and posttraumatic epilepsy (PTE).

Postconcussion Syndrome

Postconcussion syndrome is a nonspecific constellation of symptoms that commonly follow minor or seemingly inconsequential head injury, perhaps without loss of consciousness. Symptoms include headache, irritability, inability to concentrate, inattention, insomnia, memory difficulty, and nonspecific dizziness. Neurologic examination and imaging studies are normal. In most individuals, symptoms are self limited, lasting days to weeks or at most 3 to 6 months. This syndrome ordinarily does not pose long-term implications for the aviator.

Focal Neurologic Deficit

Focal neurologic deficit following TBI can take many forms, including cranial nerve palsies (olfactory nerve, optic nerve, nerves to extraocular muscles, facial nerve, acousticovestibular nerve, other), expressive aphasia, hemiparesis or other focal motor deficit, and ataxia. Most neurologic recovery occurs within 6 months, with further recovery occurring more slowly over a span of 2 to 3 years.

Neuropsychological Residual

Accelerative and rotational forces can injure brain tissue exposed to irregular bony surfaces within the cranial vault. The frontal poles and orbitofrontal surfaces of the frontal lobes may suffer contusion injury, and the anterior temporal lobes are similarly susceptible.

The frontal lobes have to do with personality, behavior, and executive functions, whereas the temporal lobes are more related to intellect and memory. Frontal lobe injury may lead to behavioral changes including disinhibition, irritability, and impaired anger control with explosive outbursts. Alternatively, an individual might exhibit apathy, indifference, and depression. Impaired judgment, planning, reasoning, abstraction, and initiation of activity may reflect impaired executive functions. Perseveration (inability to change mental set) and inability to employ a problem-solving strategy are common. Deep white matter injury may cause impaired attention and concentration. Temporal lobe injury may lead to significant memory impairment, which is often a major sequela of TBI.

The aeromedical evaluator should remain mindful of the possibility of neuropsychological impairment in persons with moderate to severe TBI. If indicated by clinical evaluation and review of records, formal neuropsychological testing might be needed.

Posttraumatic Epilepsy

A major aeromedical concern following TBI is risk of seizures. Whereas penetrating injuries involving dural laceration and violation of brain parenchyma confer a 20% to 40% risk of PTE, risk in closed head injury is approximately 5%. A history of febrile seizures, family history of seizures in a first-degree relative, cerebral contusion, and hematoma (epidural, subdural, intraparenchymal) are associated with increased risk for PTE.

An impact seizure, occurring as the name implies at the time of contact, ordinarily does not portend chronic seizure potential. Delayed seizures beginning weeks or months after TBI imply gliotic scar with risk of persistent seizure potential.

Risk of PTE increases with head injury severity (35), particularly with severe TBI. In this study by Annegers, 1-year risk with severe TBI was 6%, compared to less than 1% with mild to moderate TBI. Cerebral cortical contusion, cerebral hematoma, early seizures, loss of consciousness or PTA beyond 1 day, and depressed skull fracture are associated with increased seizure risk. The presence of subdural hematoma confers increased risk, as well as epidural hematoma to a lesser extent.

Iron compounds are important in animal models of epileptogenesis. Current thought reflects the hypothesis that PTE is an "iron-driven" phenomenon. The theory holds that extravasated red blood cells into neural tissue eventually leads to iron liberation from hemoglobin and formation of highly reactive free radical oxidants in the metabolism of iron, resulting in lipid peroxidation with injury to the cell membrane and cell organelles.

Approximately one third of individuals with PTE will have a first event within 3 months, 50% within 6 months, 75% within 1 year, and 90% within 2 years.

NEOPLASMS

Intracranial neoplasms will be encountered in aviators. Presenting symptoms of tumors may include headaches, vomiting, seizures, cognitive changes, and focal neurologic symptoms such as hemiparesis or ataxia.

Benign Neoplasms

Benign intracranial neoplasms can involve the dura, cranial nerves, or brain parenchyma (36). Extraparenchymal tumors include meningioma, acoustic neuroma, neurofibroma, and pituitary adenoma. Benign parenchymal tumors include ependymoma, colloid cyst of the third ventricle (in reality a cyst), and choroid plexus papilloma. Symptoms usually arise from compression of neural structures rather than invasion. Some benign lesions cannot be safely removed for fear of compromising major or vital structures, giving rise to the term *malignant by position*. These may include tumors involving the clivus, the cavernous sinus, and craniopharyngiomas adherent to the floor of the third ventricle. Residual tumor may lead to recurrence.

Benign dura-based tumors or cranial nerve tumors lend themselves to complete resection, particularly if removed when small. These include meningiomas overlying the cerebral cortex, acoustic neuroma, trigeminal neurofibroma, and pituitary adenoma. Colloid cysts, choroid plexus papillomas, and pinealomas can often be totally removed.

Malignant Neoplasms

Malignant intracranial neoplasms usually arise in brain parenchyma, are invasive, and have potential for rapid growth when of high grade. The gliomas (astrocytomas and oligodendrogliomas) are the most common malignant primary parenchymal tumors. The term *glioblastoma multiforme* refers to high-grade astrocytomas. Invasive features include finger-like projections of malignant cells that interdigitate with normal neural tissue. The surgeon can "debulk" the tumor, but cannot employ the principle of wide excision without compromising neurologic function.

Recurrence is the rule with gliomas, albeit possibly many years later when the tumor is of low grade. Surgical removal without recurrence is uncommon. There are exceptions, such as cystic astrocytoma of the cerebellum with mural nodule in children.

For aeromedical disposition, the evaluator must consider the nature (benign or malignant) and location of the tumor, the presenting signs, the nature and degree of residual deficit (motor, sensory, cognitive), potential for recurrence, and the possibility of seizures. As with resection of vascular malformations, complete tumor resection does not assure freedom from seizures, which may continue to arise from the altered neuronal bed of the lesion. Often a period of observation is employed. Despite apparent neurologic stability over a long period, even years, with low-grade gliomas, malignant parenchymal tumors characteristically recur, ordinarily barring medical certification.

HEREDITARY, DEGENERATIVE, AND DEMYELINATING DISORDERS

Included here for discussion are several conditions that may be nonprogressive, intermittently active and cumulatively progressive, or follow a slowly progressive temporal profile. With appropriate monitoring, medical certification may be appropriate unless and until the condition compromises aviation safety.

Familial and Essential Tremor

Essential tremor is the most common movement disorder with a reported prevalence of up to 5.6%. Familial tremor and essential tremor are the same, the only difference being the presence or absence of a family history of tremor. Autosomal dominant inheritance is present in 60% of cases (37). Although tremor may appear early in life, the mean age of onset is 35 to 45 years. Hand tremor is present in 94%, head tremor in 33%, voice tremor in 16%, and leg tremor in 12%. Slow worsening of tremor over many years is a characteristic feature.

Tremor is usually postural (voluntarily maintaining posture against gravity, such as arms outstretched) and with intention or use (directed voluntary movement toward a target). The tremor frequency is 8 to 12 Hz. Victims often describe difficulty in writing, balancing peas on a fork or soup on a spoon, carrying an empty cup on a saucer, using a screwdriver, or bringing a glass to the mouth. Rest tremor rarely occurs. Improvement with alcohol ingestion is commonly reported.

Essential/familial tremor may have aeromedical implications (e.g., difficulty targeting and manipulating small closely spaced cockpit switches). One of my patients, an airline captain, noted a vigorous shudder in his aircraft as he applied toe brakes after landing. He shut down the aircraft and had it towed to the gate, assuming a mechanical problem. Nothing was found, but recurrence on two other occasions led to identification of a foot tremor. Low-dose β-blocker treatment allowed him to complete his career.

Fortunately tremor causes little or no impairment in most individuals, progressing very slowly and perhaps not requiring treatment. If treatment is warranted, β-blockers are often highly effective. Primidone, an older anticonvulsant, is useful in pediatric dose ranges. However, primidone is a barbiturate derivative that can cause drowsiness, barring its use in the aviation environment. Gabapentin and benzodiazepines are also precluded because of potential central nervous system effects.

Parkinson's Disease

Parkinson's disease is characterized by a classic triad of symptoms including tremor at rest, muscular rigidity, and slowness of movement (bradykinesia). Common clinical features include a slow-shuffling gait, freezing or gait arrest, a general attitude of flexion, impaired postural reflexes, diminished vocal volume, and paucity of facial expression (mask-like facies). These features are observed by the examiner, and neurologic examination usually discloses cogwheel rigidity and impaired rapidly alternating movements (foot tapping, finger wiggle, pronation–supination).

An individual may seek medical attention early in the course of the illness for purposes of identifying the condition, but with no desire or need for treatment. Aeromedical certification may be allowed with appropriate monitoring mechanisms for progression. When treatment is indicated, potential side effects of medication warrant consideration.

Anticholinergics, with their attendant risk of drowsiness and cognitive changes, were the only agents available for treatment until the advent of levodopa in the late 1960s. Levodopa remains the gold standard treatment, and many individuals function well with this agent, remaining relatively free of side effects. In later years, dopamine agonists, primarily pramipexole and ropinirole, came into favor as initial treatment, adding levodopa later if necessary. These agents were initially approved for use by the Federal Aviation Administration (FAA), but due to reports of excessive daytime sleepiness approval was withdrawn. Amantadine has been employed for treatment of tremor, and entacapone delays the breakdown of dopamine in individuals taking levodopa.

Some individuals with Parkinsonian symptoms exhibit evidence of a more widespread cerebral disturbance, giving rise to the term *Parkinson-plus* syndromes. Additional features may include dementia, impaired eye movements, ataxia, orthostatic hypotension, and dysautonomic manifestations. Multiple system atrophy and progressive supranuclear palsy are examples. The neurologist or movement disorder subspecialist differentiates these entities based on clinical features.

Early or mild Parkinson's disease causing little or no impairment need not preclude medical certification. Some medications, such as levodopa or amantadine, might be acceptable without significant side effects.

Multiple Sclerosis

MS is a chronic disease affecting young- and middle-aged adults with slight female preponderance. The illness is characterized by multiple lesions of the nervous system, separated by space and by time. Lesions in MS consist of plaques, localized areas of inflammation, demyelination, and glial scarring involving the white matter of brain and spinal cord. Episodes of demyelination and remyelination account for the exacerbations and remissions commonly seen in MS.

The clinical course of MS may vary among individuals. In primary progressive MS, the disease follows a slowly progressive clinical course without interruption. In the more commonly encountered relapsing and remitting variety of MS, the characteristic exacerbations and remissions occur. Each exacerbation may incompletely resolve, resulting in cumulative neurologic deficit. In secondary progressive MS, a relapsing and remitting clinical course gives way to a slowly progressive decline in neurologic function in later years.

Clinical manifestations of MS can be highly variable depending on plaque distribution in brain and spinal cord. Unilateral optic neuritis is a common presenting sign of MS. Other symptoms might include diplopia, dysarthria, ataxia, motor or sensory symptoms, and bladder or bowel dysfunction. Approximately 14% of individuals with MS have mild or inconsequential neurologic deficit, giving rise to the term *benign MS*.

Acute exacerbations are commonly treated with intravenous corticosteroids, specifically methylprednisolone. Immunomodulatory therapy is employed in an effort to reduce the frequency and severity of exacerbations and slow the accumulation of neurologic deficit. Therapy consists of parenteral administration of an interferon preparation or glatirimer acetate. In individuals with significant progression despite steroids and immunomodulatory therapy, chemotherapeutic agents may be employed and agents that are prescribed include cyclophosphamide, azothioprine, methotrexate, and novantrone.

Aeromedical disposition may be favorable in some individuals with MS. Persons with "benign MS" may present no risk to aviation safety. Some with slowly progressive MS, and others with widely separated and relatively minor exacerbations without accumulation of significant neurologic deficit might warrant consideration. Others with significant functional disability, symptoms clearly related to aviation safety (e.g., vertigo, diplopia, cognitive change, etc.), or frequent severe exacerbations will not be candidates for medical certification.

CAVEATS IN NEUROLOGIC AEROMEDICAL DISPOSITION

In neurologic diagnosis, a frequently occurring and vexing problem is the proper interpretation of ancillary studies. This is of utmost importance in aeromedical disposition because an inadequate or inaccurate history coupled with a misinterpreted laboratory study can erroneously hamper or end an aviation or space career. Interpretations that commonly confound neurologic diagnosis include those of HUT, EEG, and MRI studies.

Head-Up Tilt Studies

As mentioned in the section **Syncope** in this chapter, HUT studies may aid the evaluation of unexplained syncope. Kapoor reported approximately 50% of patients with unexplained syncope have a positive response to passive tilt testing (38). In that study, two thirds of positive responses occurred with pharmacologic activation (isoproterenol) as opposed to passive tilt. However, a significant proportion of asymptomatic individuals may have a positive response. Kapoor and Brant reported a false-positive rate of 20% without pharmacologic evaluation and 31% with isoproterenol activation (39). Reproducibility is another issue. In a study involving 109 subjects undergoing HUT on 2 consecutive days, Brooks et al. reported a high degree of variability in responses to HUT, with frequent nonreproducibility of vasodepressor responses on the second day (40). Reproducible vasodepressor responses occurred in only 11 of 36 subjects (31%).

The aeromedical evaluator must be cautious in coupling a false-positive tilt table response with a nonsyncopal neurologic event, such as seizure. Such errors have occurred.

Electroencephalogram

In the general population, there is a 10% to 15% incidence of minor nonspecific EEG abnormalities, and 2% to

3% of the population demonstrates moderate abnormalities (41). These changes may also occur in the presence of disease, and careful clinical judgment is necessary in determining their significance, if any. The aerospace medicine physician must be particularly cautious when attempting to couple reported EEG abnormalities with clinical events.

For example, a nonspecific EEG abnormality appearing in an individual with syncope accompanied by twitching and incontinence may lead to an erroneous diagnosis of epilepsy with its far reaching implications.

The aeromedical evaluator must keep in mind that individuals without seizures may demonstrate epileptiform abnormalities on EEG, whereas individuals with epilepsy (fits) may have persistently normal EEGs (spikes without fits and fits without spikes). Engel notes that 2% of the population demonstrates specific epileptiform abnormalities on EEG (42). This may lead to an inappropriate diagnosis of epilepsy.

It is well known that a significant proportion of individuals with epilepsy have a normal EEG (42–44). Studies in the literature report that 50% to 60% of routine EEGs (30-minute routine recordings without sleep deprivation), obtained after a seizure in patients later clearly diagnosed as having epilepsy, demonstrate epileptiform abnormalities (45). Activation techniques including hyperventilation, photic stimulation, sleep recording, and sleep-deprived recording may increase the yield. Interictal EEG abnormalities may be intermittent, and a 30-minute recording is a small sample of a 24-hour day. Serial EEG recordings may also increase yield, but little further yield is obtained after four recordings (46). It is important for the EEG interpreter to state that a normal EEG does not exclude the possibility of epilepsy, as well as mentioning sampling effect (47). In difficult cases, sustained video-EEG recording (days or more) can be accomplished in an epilepsy monitoring unit.

Lastly, there are known benign EEG patterns with epileptiform morphology that might be interpreted by less-experienced clinicians as being significant. Examples include 14 and 6 Hz positive spikes, small sharp spikes, 6 Hz spike and wave, and wicket spikes (47). These patterns can be seen in normal individuals.

Magnetic Resonance Imaging

A frequently occurring finding in cerebral MRI is the presence of T2 hyper intense lesions, commonly referred to as *unidentified bright objects* (UBOs), or *nonspecific white matter hyperintensities* (WMHs). The reporting of these lesions may lead to diagnostic uncertainty for the aeromedical examiner (AME)/flight surgeon and have far reaching implications for the aviator or astronaut if interpreted wrongly. A fully trained and experienced neuroradiologist might report "normal" findings, whereas other interpreters might report concern for small vessel cerebrovascular disease (multi-infarct state) or demyelinating disease (MS).

In one study, UBOs were present in 5.3% of healthy individuals aged 16 to 65, but were less common in younger individuals (48). In another study, pathologic features of T2 silent WMHs in patients without neurologic signs or symptoms represented myelin pallor associated with vessels showing hypertensive and arteriosclerotic changes (49). Others feel the lesions represent dilated normally occurring perivascular (Virchow-Robin) spaces. UBOs occur with greater frequency in individuals with migraine (50).

The neurologic literature reflects considerable debate regarding the nature and significance of UBOs. The debate is also reflected in practice, as evidenced by variable interpretations among general radiologists, neuroradiologists, neurologists, and neurosurgeons. The aeromedical evaluator with less frequent exposure to MRI is further disadvantaged. One can only advise that the ability to distinguish between nonspecific WMHs (UBOs, WMHs) and disease-specific white matter lesions is an important consideration for the clinician. As in other ancillary studies, the test must be interpreted in the context of the patient and the clinical setting.

REFERENCES

1. Wiebers DO, Dale AJ, Kokmen E, et al. eds. *Mayo clinic examinations in neurology*, 7th ed. St. Louis: Mosby, 1998:3.
2. Raskin NH. Paroxysmal disorders: migraine and other headaches. In: Rowland LP, ed. *Merritt's textbook of neurology*, 9th ed. Baltimore: Williams & Wilkins, 1995:838.
3. Trimble MR. Psychiatry and neurology: neurologic presentations of psychiatric illness. In: Aminoff MJ, ed. *Neurology and general medicine.* 2nd ed. New York: Churchill Livingstone, 1995:482.
4. Hodges JR. *Transient amnesia, clinical and neuropscyhological aspects*. London: WB Saunders, 1991.
5. Dermkasian G, Lamb LE. Syncope in a population study of healthy young adults. *JAMA* 1958;168:1200–1207.
6. Grow MC, Armstrong HG. *Fit to fly*. New York: D. Appleton-Century, 1942:62.
7. Olashanksy B. Syncope: overview and approach to management. In: Grubb BP, Olshansky B, eds. *Syncope: mechanisms and management*. New York: Futura Publishing, 1998:33.
8. Hauser WA, Hesdorffer DC. Incidence and prevalence. *Epilepsy: frequency, causes and consequences.* New York; Demos, 1990:1.
9. Hauser WA, Rich SS, Annegers JP, et al. Seizure recurrence after a first unprovoked seizure: an extended follow up. *Neurology* 1990;40:1163–1170.
10. Van Donselaar CA, Schimisheimer RJ, Geerts AT, et al. Value of the electroencephalogram in adult patients with untreated idiopathic first seizures. *Arch Neurol* 1992;49:231–237.
11. Sacco RL, Adams R, Albers G, et al. Guidelines for prevention of stroke in patients with ischemic stroke or transient ischemic attack: a statement for health care professionals from the American Heart Association/American Stroke Associationn council on stroke. *Stroke* 2006;37:577–617.
12. Fleming KD, Brown RD, Petty GW, et al. Evaluation and management of transient ischemic attack and minor cerebral infarction. *Mayo Clin Proc* 2004;79(8):1071–1086.
13. Fleming KD, Brown RD. Secondary prevention strategies in ischemic stroke: identification and optimal management of modifiable risk factors. *Mayo Clin Proc* 2004;79(10):1330–1340.
14. Gorelick PB. Stroke prevention. *Arch Neurol* 1995;52:347–355.
15. PROGRESS Collaborative Group. Randomized trial of Perindopril based blood-pressure-lowering regimen among 6,105 individuals with previouis stroke or transient ischemic attack. *Lancet* 2001;358:1033–1041.

16. Chobanian AV, Bakris GL, Black HR, et al. National high blood pressure education program coordinating committee. The seventh report of the Joint National Committee on Prevention, Detection, Evaluation and Treatment of High Blood Pressure: the JNC-7 report. *JAMA* 2003;289:2560–2572.
17. Fine-Edelstein JS, Wolf PA, O'Leary DG, et al. Precursors of extracranial carotid atherosclerosis in the Framingham study. *Neurology* 1994;44:1046–1050.
18. Wilterdink JL, Furie KL, Easton JD. Cardiac evaluation of stroke patients. *Neurology* 1998;51(Suppl 3):S23–S26.
19. Dodick DW, Meissner I, Meyer FB, et al. Evaluation and management of asymptomatic carotid artery stenosis. *Mayo Clin Proc* 2004;79(7):937–944.
20. Sacco RL, Shi T, Zamanillo MC, et al. *Predictors of mortality and recurrence after hospitalized cerebral infarction in an urban community: the Northern Manhatton stroke study*. *Neurology* 1994; 44(4):626–634.
21. Dhamoon MS, Sciacca RR, Rundek T, et al. Recurrent stroke and cardiac risks after first ischemic stroke: the Northern Manhattan study. *Neurology* 2006;66(5):641–646.
22. Hardie K, Hankey GJ, Jamrozik K, et al. Ten-year risk of first recurrent stroke and disability after the first-ever stroke in the Perth Community Stroke Study. *Stroke* 2004;35:731–735.
23. Modrego PJ, Mainar R, Turull L. Recurrence and survival after first-ever stroke in the area of Bajo Aragon, Spain. A prospective cohort study. *J Neurol Sci* 2004;224(1–2):49–55.
24. Hillen T, Coshall C, Tilling K, et al. Cause of stroke recurrence is multifactorial: patterns, risk factors, and outcomes of stroke recurrence in the South London stroke register. *Stroke* 2003;34(6):1457–1463.
25. Staaf G, Lindgren A, Norrving B. Pure motor stroke from presumed lacunar infarct: long-term prognosis for survival and risk of recurrent stroke. *Stroke* 2001;32(11):2592–2596.
26. Ory F, Albucher JF, Guiraud-Chaumeil B, et al. Risk of recurrent stroke in adults aged under 45 years following a first ischemi stroke: a five-year study of 95 patients. *Rev Neurol* 2003;159(8–9):755–760.
27. Kittner SJ, Stern BJ, Wozniak M, et al. Cerebral infarction in young adults. The Baltimore-Washington cooperative young stroke study. *Neurology* 1998;50:890–894.
28. Verona JF, Bermejo F, Guerra JM, et al. Long-term prognosis of ischemic stroke in young adults. Study of 272 cases. *J Neurol* 2004;251(12):1507–1514.
29. Musolino R, La Spina P, Granata A, et al. Ischemic stroke in young people: a prospective and long-term follow up study. *Cerebrovasc Dis* 2003;15(1–2):121–128.
30. Sacco RL, Ellenberg JH, Mohr JP, et al. Infarcts of undetermined cause: The NINCDS stroke data bank. *Ann Neurol* 1989;25:382–390.
31. Demaershcalk BM. Literature-searching strategies to improve the application of evidence-based clinical practice principles to stroke care. *Mayo Clin Proc* 2004;79(10):1321–1329.
32. Case CS, Mohr JP, Caplan LR. Clinical manifestations of stroke: intracranial hemorrhage. In: Barnett HJM, Mohar JP, Stein BM, et al. eds. *Stroke: pathophysiology, diagnosis and management,* 2nd ed. New York: Churchill Livingstone, 1992:561.
33. Mohr JP, Hilal SK, Stein BM. Clinical manifestations of stroke: arteriovenous malformations and other vascular anomalies. In: Barnett HJM, Mohar JP, Stein BM, et al. eds. *Stroke: pathophysiology, diagnosis and management,* 2nd ed. New York: Churchill Livingstone, 1992:659.
34. Mohr JP. Clincal manifestations of stroke: intracranial aneurysms. In: Barnett HJM, Mohar JP, Stein BM, et al., eds. *Stroke: pathophysiology, diagnosis and management*, 2nd ed. New York: Churchill Livingstone, 1992:617.
35. Annegers JF, Hauser WA, Coan SP, et al. A population-based study of seizures after traumatic brain injuries. *N Engl J Med* 1998;338(1):20–24.
36. Shou SN, Kramer RS, Shapiro WR. Neurological and neurosurgical conditions associated with aviation safety: intracranial tumors—panel 2. *Arch Neurol* 1979;36:739.
37. Deuschl G, Krack P. Tremors: differential diagnosis, neurophysiology, and pharmacology. In: Jankovic J, Tolosa E, eds. *Parkinon's disease and movement disorders.* Baltimore: Lippincott Williams & Wilkins, 1998:429.
38. Kapoor WN, Smith M, Miller NL. Upright tilt testing in evaluating syncope: a comprehensive literature review. *Am J Med* 1994;97:78–88.
39. Kapoor WN, Brant N. Evaluation of syncope by upright tilt testing with isoprot erenol. *Ann Droit Int Med* 1992;116:358–363.
40. Brooks R, Ruskin JN, Powell AC, et al. Prospective evaluation of day-to-day reproducibility of upright tilt-table testing in unexplained syncope. *Am J Cardiol* 1993;71:1289–1292.
41. Aronson AE, Auger RG, Bastron JA, et al. Chapter 15:Electroencephalography. In: *Mayo clinic examinations in neurology*, 5th ed. Philadelphia: WB Saunders, 1981:287.
42. Engel J Jr. *Seizures and Epilepsy*. Philadelphia: FA Davis, 1989: 313.
43. Ajmone Marsan C, Zivin LS. Factors related to the occurrence of typical paroxysmal abnormalities in the EEG recordings of epileptic patients. *Epilepsia* 1970;11:361–381.
44. Gumnit RJ. *The Epilepsy handbook. The practical management of sezures*, 2nd ed. New York: Raven Press, 1995:5.
45. Leppik IE. *Contemporary diagnosis and management of the patient with Epilepsy*, 6th ed. Newtown: Handbooks in Health Care, 2006:61.
46. Salinsky M, Kanter R, Dasheiff R. Effectiveness of multiple EEG's in supporting the diagnosis of epilepsy: an operational curve. *Epilepsia* 1987;28:331–334.
47. Daly DD, Pedley TA. *Current practice of clinical electroencephalography*, 2nd ed. Philadelphia: Lippincott-Raven, 1997:316.
48. Hopkins RO, Beck CJ, Burnett DL, et al. Prevalence of white matter hyperintensities in a young healthy population. *Neuroimaging* 2006;16(3):243–251.
49. Takao M, Koto A, Tanahashi N, et al. Pathologic findings of silent hyperintense white matter lesions on MRI. *J Neurol Sci* 1999;167(2):127–131.
50. Porter A, Gladstone JP, Dodick DW. Migraine and white matter hyperintensities. *Curr Pain Headache Rep* 2005;9(4):289–293.

RECOMMENDED READINGS

Aminoff MJ, ed. *Neurology and general medicine*, 2nd ed. New York: Churchill Livingstone, 1995.

Rowland LP, ed. *Merritt's textbook of neurology*, 9th ed. Baltimore: Williams & Wilkins, 1995.

Wiebers D, Dale AJD, Kokmen E, et al. eds. *Mayo clinic examinations in neurology*, 7th ed. St. Louis: Mosby, 1998.

CHAPTER 17

Aerospace Psychiatry

David R. Jones

> But let us set before the eyes of the mind a much more lovely spectacle . . . in which people, who while still alive become earthly gods rising on a golden chain toward Heaven . . . who know all arts and sciences . . .
>
> —*Johann Daniel Major, 1670 (1)*

> God denied to men the faculty of flight so that they might lead a quiet and tranquil life, for if they knew how to fly they would always be in perpetual danger.
>
> —*Johann Caramuel Lobkovitz, 1670 (1)*

> . . . flying is not dangerous, it is interesting.
>
> —*Richard Bach, 1963 (2)*

Aeromedical practitioners (civilian aviation medical examiners and military flight surgeons) select fliers and maintain their physical health in a manner that differs considerably from the conventional practice of clinical medicine. Likewise, aerospace psychiatry affirms normal cognition, emotional stability, coping skills, and behavior as defined in terms of flying safety and effectiveness, thereby differing from the primary concerns of clinical psychiatry with the diagnosis and treatment of mental disorders.

Flying is more than a means of transportation. Most writings of early aviators and the physicians who worked with them note that safe and effective flying involves more than simply having the desire and the physical capacity to fly. The terms used to describe the mental, emotional, and psychologic factors involved in aviation have varied considerably over the years, but the existence of these necessary qualities has never been in doubt. Three of the nine chapters in Anderson's early book on aviation medicine discussed such matters as "the psychology of aviation," and "the aeroneuroses." "Nervous breakdowns have been noted since the early days of flying. In fact, they may be classed as an occupational neurosis [in] a comparatively new occupation, namely: aviation" (3).

Aircraft and their missions have changed since the days of wood, wires, and dope-covered linen, and the pilot population also has changed. Whereas our predecessors supported a homogeneous group of young men and a few young women, now we must consider people of all ages flying in general aviation, commercial aviation, peacetime or combat military aviation, and short- or long-duration space missions. Aeromedical practitioners still seek to select prospective fliers with healthy motivation, adequate innate physical and mental abilities, stable temperaments, and adaptive coping skills, but now we must maintain or enhance these characteristics throughout flying careers of 50 years or more.

Fliers writing about aviation may discuss matters that involve what we now call "human factors" (see Chapter 24) but they also discuss, in some way or other, the pure joy of flying: the positive emotional factors that form an inescapable and essential part of the reasons that fliers love to fly. No other word will do. Fascination with the idea of flight is as old as the human race. Primal themes include the idea of the air as a living female entity. Air stimulates the imagination because it is invisible, unpredictable, and exists between heaven and earth. Invisible beings with the power of flight seem to inhabit this realm: angels, fairies, sylphs, winged demons, and the like. No religion or mythology fails to discuss or illustrate the existence of such creatures. The very concept of "up" involves becoming closer to heaven, as shown in the writings of St. Augustine, and the spirits of the air could move so speedily that they could appear to predict events (1). Armstrong (4) related the emotional aspects of aviation to a spiritual experience, noting that all religions portray flight as a divine gift. In the oft-quoted words of Magee's sonnet "High Flight," the ultimate act of the flier is to "Put out my hand and touch the face of God" (5). Military aviators, a traditionally unemotional group, give each other plaques inscribed with this poem. In short, psychologic factors are intrinsic to aviation.

Medical literature, by its nature, tends to discuss things that go wrong. The medical specialty of clinical psychiatry deals with mental disorders: their causes, diagnoses, and treatments, as well as their preventive aspects. Aerospace psychiatry differs from clinical psychiatry in several ways. Stated succinctly, not all mentally normal people are fit to fly, and not all mental disorders necessarily render a pilot unfit to fly. Aerospace psychiatry must deal with positive as well as negative mental health matters, for the absence of positive mental attributes, by no means definable as a mental disorder, may degrade safe and effective flying as surely as the presence of mental disease. Psychiatric disorders in fliers can affect flying safety and effectiveness at subclinical levels that do not warrant formal psychiatric diagnoses in nonfliers. Aerospace psychiatry also involves the system of physical examinations that certifies fliers for specified periods, examinations that include a prediction that the flier will remain mentally fit to fly at least until the next evaluation. In some military and commercial settings, the examiner may also be charged with selecting fliers who will be able to fly for a full career, that is, for 20 years or more, or until retirement age. This long-term requirement stands in stark contrast to the difficulty that clinical psychiatrists face in predicting whether a depressed patient will become suicidal in the next few weeks.

Operational aeromedical practitioners make psychiatric decisions about fliers in their offices. These practitioners may have varying levels of psychiatric experience and skill. Aerospace medicine describes the world of the aviator in ways that do not allow for easy translation into psychiatric terms, and so a flight surgeon and a clinical psychiatrist may describe the same phenomenon in quite different ways. Close coordination and cooperation is essential between the practitioners of aerospace medicine and their mental health consultants who may have varying knowledge of, or interest in, the aeromedical aspects of the matter in question. Flight surgeons' decisions about fliers are not based on the usual clinical indications alone, but also on the aeromedical implications. Most psychiatrists would not understand the implications of "thinking ahead of the aircraft," "get-home-itis," or "poor situational awareness" without considerable explanation. Only a few physicians have trained and practiced in both fields to the extent that they may make aeromedical judgments about patients suffering from mental disorders without consultation.

Need for interdisciplinary cooperation arises in part because some fliers react quite differently to aviation stressors than they do to life stressors. Mental health factors that would be of little concern in everyday life—this defines *subclinical*—may compromise aviation safety and effectiveness in ways of which a non–aviation-oriented physician, psychologist, or counselor may simply be unaware. Human lives involve infinite circumstances of thought and behavior, which by definition may never all be included in a set of regulations. Therefore, knowing which problems are not compatible with safe and effective flight calls for a mature professional understanding of the principles underlying aeromedical decisions concerning mental health.

A textbook that is used by aeromedical practitioners in different countries should point out that cultural differences will affect some of the matters discussed in this chapter (e.g., attitudes toward women pilots or toward the treatment of symptoms of acute stress reactions in combat). In presenting the mental health aspects of selection, health maintenance for safe and effective flying, reactions to stressors of life and of aviation, and other aeromedical topics, we will discuss useful principles rather than explicit answers that may not fit the reader's circumstances, or that may quickly become obsolete.

SELECTION OF FLIERS

Aeromedical mental health standards should pertain to flying safety and effectiveness, or to the health of the flier. Each criterion should be carefully justified because as more standards are used for selection less people can meet them all. Failing to meet a criterion may disqualify a person from employment, and so each standard must meet metastandards of fairness, validity, and equity. Valid standards should address safety, health, dependability, and competence, and the factors examined should be as objectively measurable and reproducible as possible. The ultimate validation of mental health in aviation is the flier's career-long health, safety, and effectiveness. Researchers studying the effectiveness of various selection techniques have used different outcome criteria: solo flight, graduation from training, accident rates, and the career progression of graduates for up to 5 years. Any comparative assessment of this research must consider these different criteria. Some selection processes seek to identify those who are fully qualified to fly by disqualifying only those who have disorders (select-out), and some seek the best qualified among those who are not disqualified (select-in) (6).

Mental health standards continue to evolve as the mental health disciplines advance from their subjective historical roots toward objective measurements of mental function (psychologic and neuropsychologic testing), and toward an empirical foundation for classification of mental disorders, as described in the *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition* (*DSM-IV*) of the American Psychiatric Association (7, (p. xv). Advanced methods of examining the central nervous system [functional magnetic resonance imaging, positron-emission tomography, single-proton emission tomography, and technologically enhanced (quantitative) electroencephalography] offer diagnostic precision, and some may eventually become practical selection tools. Future genetic research may help identify the functional origins of the temperamental qualities of successful aviators. For now, though, most authorities depend on interviews and psychological tests for aeromedical qualification of prospective fliers and leave their operational selection to the intuition and experience of flight instructors. The selection process may be divided into matters involving motivation, aptitude for the job (ability), and sensitivity to self and others (stability) (6, (pp. 100–111).

Motivation to Fly

Motivation is the psychic force or energy that moves a person to satisfy a yearning or to achieve a goal. Healthy motivation to fly resembles a motivation for an artistic career or a career in medicine in its combination of emotional (limbic, irrational) and cognitive (cortical, rational) components. Many pilots will say, "I've wanted to fly for as long as I can remember," which is evidence of the deep roots of their motivation. The proportion of emotional and cognitive elements in a specific flier changes with age, experience, and other life factors such as marriage, children, and normal events of life. A flier's answer to the question "What do you tell yourself about the dangers of flying?" change after a crash, after marriage or the birth of a baby, or simply as the flier ages. Therefore, motivation to fly should be regarded as a dynamic process that may be reassessed when aeromedically necessary.

Motivation to fly may represent equilibrium between positive factors (e.g., joy, emotional meaning, and coping skills), and negative factors (e.g., fear, anxiety, and experienced or anticipated danger). The pure emotional joy of flying offsets a healthy fear of its true dangers. The subconscious "meaning" of flying (it represents power, freedom, independence, control, and other basic urges) can also give rise to anxiety if these primal elements are threatened. This may occur if the flier senses a loss of control over life situations (marital or family discord), resulting in a phobic fear of flying (FoF). Finally, the flier's coping skills, necessary for basic resilience, hardiness, and stress tolerance, may be overcome by the actual dangers of flight as encountered in near collisions, accidents involving oneself or respected friends, or in combat situations where control is impossible (8,9).

Some fliers choose to fly not because of an emotional attraction, but because of a more rational attraction (e.g., financial rewards, social status, or travel). Because they do not have a strong emotional commitment to flying, these "rational choice" fliers may move on to other careers or activities without much internal struggle (symptoms) when their life circumstances change or when the real dangers of flight exceed their perception of the rewards of flying. A survey by McGlohn et al. (10) contrasted the mix of emotional and rational motivational elements in male and female U.S. Air Force aviators. The reasons most endorsed by the men (45%) emphasized the emotional elements that attracted them to aviation, whereas those most endorsed by the women (34%) emphasized the rational elements.

Any assessment of a person's motivation to fly must deal with basic emotional issues involving "flying and dying." Flying, a fascinating, dangerous activity, is both loved and feared—loved because of its power, grace, and beauty; feared because of the chance of catastrophe (11). Fliers who value their appearance of rationality and coolness may speak in unemotional terms about aviation matters that in fact have deep emotional roots. Because fliers by inclination and culture tend to downplay (suppress) emotional matters, or to compartmentalize (deny or even repress) them entirely, they may not recognize the strength of these issues in their own lives. Aeromedical practitioners must consider possible emotional factors whenever a flier's response to a situation does not make sense (is irrational), or involves an inappropriate emotion, or seems disproportionate to the stressor involved. These three factors—irrationality, inappropriateness, and disproportionality—indicate underlying emotional components of aviation-related symptoms.

Some fliers have a flawed or pathologic motivation to fly. A need to compete with a fearful father figure through aggressive activity carries with it the unconscious fear of retribution should the effort succeed. Such individuals may become increasingly anxious as they move toward their goal of becoming an aviator. Others may be living out a parent's own fantasy, or trying to prove that they are not afraid although no one said they were (counterphobic), or seeking risks in search of thrills (high stimulus threshold). A few would-be pilots do not wish to fly for its own sake, but wish to attain the role of pilot to compensate for feelings of inadequacy. Seeing themselves as alienated from others, inept, or weak, they wish to acquire the gregarious, competent, and powerful attributes they perceive to be those of fliers. Such pathologic motivations may underlie significant symptoms or downright dangerous flying behaviors in the absence of diagnosable psychiatric disorders. Weak or flawed motivation, or poor defenses against the real dangers of flying, may be recognized during flight training as "manifestations of apprehension," or early in an active flying career as "FoF."

Ability to Fly

"Ability" involves a flier's physical, cognitive, autonomic, neurophysiologic, and psychologic traits. These include situational awareness, spatial perception, capacity for mental calculation, suppression of emotional responses during urgent situations in favor of analysis and correct action, psychomotor skills ("good hands"), and alertness to a wide range of sensory inputs, along with the ability to screen out stimuli of no aeronautical importance. No one can excel in all these areas, but safe and effective flight requires a balance of such capabilities; flying requires more than clinical psychiatric normality.

Abilities vary, and their assessment is not primarily aeromedical. Flight instructors can identify students with "good hands" during flight training, a crucial part of the select-in process that complements the medical process. They appraise the *in vivo* cockpit performance of applicants in matters involving intelligence, perception, attention, interpretation, and the speed and quality of decisions, based on variable sensory stimuli under flight training stress. These attributes are elemental to the ability to perform the mental and physical processes necessary for safe flight.

Aeromedical specialists and aviation psychologists have worked for decades to isolate these specific abilities and this process will undoubtedly continue for decades to come. Recent advances in flight simulator technology are challenging the conventional wisdom that only experience in actual flight can teach a person to fly. However, even the most sophisticated devices cannot duplicate fully the physical sensations and sensory inputs of actual flight (e.g., gravitational forces, pressure changes, total range of sound and vibration), nor can they overcome the student's underlying knowledge that a mistake in simulated flight may be embarrassing, but will not result in sudden death. This surety means that the student does not experience the full effect of the powerful emotional, autonomic, and hormonal stimuli that may occur when the same situation occurs in a real aircraft, just as simulated combat training cannot entirely prepare anyone for the real thing (12).

Stability

"Stability" involves personality, temperament, and interpersonal relationships, including attitude toward authority. Even a lone private pilot must decide when and where to fly, must share airways, and must adhere to flying regulations and instructions. The aviator's general attitude toward flying involves a way of thinking about weather, time of day or night, fatigue, circadian rhythm, readiness to deal with sudden inflight emergencies, and a host of other factors well known to pilots. Collectively, these are part of what the aviation community calls "human factors." A pilot's mistake in such matters can be as suddenly lethal as a midair collision, and skilled pilots have died from such avoidable choices as knowingly flying into thunderstorms or failing to perform complete preflight walk-around inspections because they were in a hurry.

Consideration of aviator stability includes an appraisal of personality (temperament). Probably no occupation has attracted as many studies of the personalities of its participants as has aviation. Beaven mentioned control of the imagination, patience, and a strong motivation to fly as important during World War I (13). Fine and Hartman emphasized above-average intelligence, a matter-of-fact view of life, and a preference for action over introspection; this latter characteristic explains why some fliers tend to act out their interpersonal frustrations rather than considering possible solutions (14). A study of 105 successful male military pilots noted their self-confidence, desire for challenge and success, and strong identification with their fathers. They tended to be eldest sons, to make life choices on a consciously rational basis, and to take risks only when their assessment of the odds led to a high chance of the desired outcome. They made friends easily, but avoided dependency and thereby maintained interpersonal distance (15). Christy described the balance between factors such as rigidity and flexibility, and the need for maturity, good motivation, and self-confidence, qualities that likely would assure success in any field of endeavor (16).

Modern research into the temperaments of successful aviators uses a more disciplined terminology. It does not depend on the clinical psychiatric literature for its vocabulary, nor does it follow the older aeromedical literature practice of describing fliers' personalities by using everyday words rather than strictly defined and measurable terms. Helmreich et al., in their research into crew resource management (CRM), have identified two personality dimensions that affect aircrew performance: *instrumentality*, the work orientation, mastery of tasks, and desire to achieve; and *expressivity*, which includes interpersonal communications and sensitivity (17). They used interviews, questionnaires, and video techniques that allowed careful analysis by investigators, instructors, and the aircrew themselves. This research has produced information about effective and ineffective aviator personalities, although the investigators have not presented their results in clinical terms. Fliers may manifest instrumentality or expressivity either positively or negatively, and both factors are important in cockpit transactions.

The CRM approach has identified three categories of aviators. The first has positive elements in both dimensions. Positive instrumentality means a strong work orientation, drive to achieve, and drive to master the task. Positive expressivity includes low competitiveness and low verbal aggression. This combination seems the best for multicrew cockpits. During CRM training, such crews have the highest scores on coordination and communication skills, and best manifest the desirable attitude that responsibility rests with the entire crew rather than with the leader. They develop the most judgment and insight about their own reactions to stressors.

Crews demonstrating high instrumentality and low expressivity have the positive instrumentality characteristics of the first group, but are competitive and verbally aggressive (negative expressivity), are less skilled in communication and coordination, learn little about command responsibility, and show only modest recognition of stressor effects. A third group of aviators has both low instrumentality and low expressivity. This group does poorest in communication and coordination, actually regresses in appreciation of collective responsibility during training, and shows little recognition of personal stressor effects (17).

Helmreich's research uses the methods of industrial or occupational psychology. The utility of the CRM concept has led to its application to other fields, such as the interactions of nuclear reactor control teams and the relationships between surgeons and anesthesiologists in operating rooms.

Selection Process

Mental health evaluations of aviators differ from usual clinical psychiatric interviews. Aeromedical examiners seek not only to affirm mental health in the ordinary sense, but also to determine when a normal person has the motivation, ability, stability, maturity, attentiveness, perception, anticipation, and judgment to make good decisions before and during a flight, and the hardiness and resilience to endure under prolonged stressors. The aeromedical practitioners responsible for physical examinations and the authorities that receive and evaluate the reports of these examinations must assess the possibility of aeromedically significant degradation of fliers during the interval until the next evaluation. In occupational selection of professional pilots, examiners must consider future fitness for a flying career of 20 years or more.

One approach to gauging the mental health of both prospective and trained aviators requires examiners to use a semistructured interview or a checklist. Flight surgeons perform formal assessments of adaptability in the U.S. Navy (Aeronautical Adaptability) (18,19) and U.S. Air Force (Adaptability Rating for Military Aviation) (20). The results vary in quality and usefulness because examiners' psychiatric interviewing and observational skills differ, as well as their time for and personal interest in such evaluations. Although any practicing physician may recognize full-blown psychiatric disorders, lesser symptoms can be difficult to detect, especially if the flier conceals the difficulties (suppression, lying) or is unaware of them (denial, repression). The little formal research on this examination technique has not confirmed its predictive value (20). Difficulties in this endeavor include subtleties of the interview process (e.g., reverse malingering or "faking good," resistances, experience of the examiner, the transference/countertransference interplay) and problems of recognizing significant symptoms and obtaining adequate and timely consultations when such symptoms are present (12).

Newly trained aeromedical practitioners soon develop professional and personal instincts about aviators, recognizing the bearing and behaviors of healthy fliers and forming useful preliminary impressions of their mental health. Some clues may be available as the examination begins: the reputation of the applicant in the community, or an examinee's interaction with office staff. Flying candidates or experienced aviators who have mental health problems may behave differently with office staff than with the examiner, and so the staff should report any behavioral problems or eccentricities to the aeromedical practitioner.

Many examinations require that the examinee fills out a form before seeing the examiner. The examinee may mark carelessly, or omit, some answers. Examiners should obtain the correct or missing data and ask why the flier made this particular mistake; because a few fliers will not wish to lie directly, but will try to avoid reporting information they regard as negative. If the applicant does not live or work locally, the examiner may ask why he or she came so far; some will "shop around" for lax examiners, or will repeat examinations to learn how to conceal disqualifying information.

Examiners also should inquire carefully into any history of consultation with mental health professionals or paraprofessionals (lay counselors, company support programs) and ask about nonprescription medications, herbal remedies, and dietary supplements. Such information may be aeromedically significant because of the nature of these remedies, or because of the symptoms for which the pilot feels they are necessary. Be alert for illogical explanations about medical history or findings. If a flier's explanation does not seem reasonable, ask for more details. If an examiner cannot understand a flier's earnest efforts at explanation, benign possibilities include misunderstandings, communicating in the flier's second language, educational deficiencies, cultural differences, or limited intelligence. However, the difficulty may be due to a neurologic or psychiatric problem.

Behaviors that caused body scars may represent patterns of personal recklessness. The scalp and skull should be palpated for evidence of head injury because these may have involved loss of consciousness or amnesia. Other pertinent physical findings bearing on mental status include unusual conduct, dress, grooming, tattoos or body piercings that suggest sociopathy, slash scars on wrists (possible suicide attempts), or stigmata of substance abuse such as odor of alcohol, needle tracks, or nasal septal scarring or perforations. The physician should talk with applicants before, during, and after the physical examination, inquiring about home, work, education, military experience, and flying activities. Again, examiners should trust their judgment that something may be amiss psychologically if they feel uneasy about the examinee.

At the end of the evaluation, the aeromedical practitioner should have enough information to decide whether a mental health disorder might be present, and whether outside medical data ought to be obtained. If anything raises clinical questions about the examinee's mental status, or even if the examiner feels uncomfortable without knowing exactly why, a brief mental status evaluation (MSE) must be performed, using some or all of the items in Table 17-1. Note that this MSE extends beyond items considered in clinical "mini-MSEs" that are limited to evaluating the sensorium rather than assessing wider aspects of cortical function. Examiners who detect possible problems should defer certification and obtain formal mental health consultation to delineate these concerns more clearly. The certifying authority may have protocols to guide this process.

Selection for Space Flight

Evaluating the mental health and temperaments of individuals seeking to become astronauts includes several factors not considered for other types of flying. The United States National Aeronautics and Space Administration's (NASA's)

TABLE 17-1

Formal Mental Status Examination ("AMSIT")

Appearance, behavior, and speech

Physical appearance: Apparent age, sex, and other identifying features. Appearance of being physically ill or in distress; and a careful description of the patient's dress and behavior.

Manner of relating to examiner: placating, negativistic, seductive; motivation to work with examiner.

Psychomotor activity: increased or decreased, including jumpiness, jiggling, tapping, looking at watch, and so on. Is the person hyperactive or lethargic?

Behavioral evidence of emotion: tremulousness, perspiration, tears, clenched fist, turned-down mouth, wrinkled brow, and so on.

Repetitious activities: mannerisms, gestures, stereotypy, "waxy flexibility," and compulsive performance of repetitious acts.

Disturbance of attention: distractibility and self-absorption.

Speech: Description—volume, rate (pressured or slowed), clarity, and spontaneity;

Disturbances—mutism, word salad, perseveration, echolalia, affectation, neologisms, and clang speech

Mood and affect (*Note*: "Mood is to affect as climate is to weather.")

Mood: use adjectives—mild (it's there), moderate (it needs treatment), or severe (it needs treatment today). Consider depression, elation, or other sustained emotions such as anger, fear, or anxiety.

Affect: its range, intensity, lability, and appropriateness to immediate thought. To describe a normal, stable emotional status, say something like, "The examinee's mood is euthymic. Affect is unremarkable in range, intensity, and stability, and is appropriate to material being discussed."

Sensorium

Orientation: for time, place, and situation.

Memory: immediate (digits recall), recent (three items for 10 min, current events), and remote (history).

Calculating ability: serial 7s, 11 times 13 out loud (valid only if patient is adequately educated).

Concentration: spell *world* backward, then arrange its letters alphabetically; repeat with *earth.*

Intellectual function

Estimate current level of function as above average, average, or below average based on general fund of information, vocabulary, and complexity of concepts. Do not confuse intelligence with education. Can the examinee handle abstract ideas, reason by analogy, "make the connection" in conversation? Is the examinee about as smart as the examiner?

Thought

Coherence: clear thoughts may be expressed incoherently.

Logic: even clear, grammatical speech may express illogical thoughts.

Goal directedness (has a point and makes it): tangential or circumstantial thought.

Disturbance of attention: distractibility (interrupts own sentences), self-absorption.

Associations: loose associations, blocking of obvious ideas or connections, and flight of ideas

Perceptions: hallucinations (false perceptions), illusions, depersonalization, and distortion of body image.

Delusions: false interpretations of real situations.

Other content: noteworthy memories, thoughts, and feelings; suicidal or homicidal intent.

Judgment: formal (specific set-piece situations such as "mailing a letter you find on the street") and social (how examinee behaves with examiner, how examinee "reads" other people—as predictable or unpredictable, reasonable or irrational, comfortable or threatening).

Abstracting ability: ask pilot to define similarities/differences between *tree–bush, child–midget, king–president, character–personality*. This is more reliable than interpreting proverbs (stitch in time, bird in the hand).

Insight: understanding of any personal dysfunction affecting self or others and its need for treatment; insight is lacking if there is an unacknowledged problem, superficial if it is only acknowledged ("It is a problem"), moderate if it is personalized ("I have a problem"), and profound if the person takes responsibility ("It's my problem, and it's up to me to fix it")

AMSIT, appearance, mood, sensorium, intelligence, and thought.

(This version of the AMSIT is adapted and reprinted from a formulation by Fuller DS. In: Leon RL. *Psychiatric interviewing: a primer*, 2nd ed. New York: Elsevier/North-Holland, 1982:75–77; with permission.)

intensely competitive biannual selection process may involve more than 3,000 initial applicants for 20 openings. The primary screening involves record reviews, but the final selection requires personal interviews and psychological testing. Almost any past or present psychiatric diagnosis will be grounds for disqualification, the binding select-out process. Mental health select-in is by no means binding because other medical and occupational standards will be applied to the applicants. However, the selection committee may consider identifiable positive personal qualities in its deliberations. Applicants are considered not only on the basis of their success in earth-bound occupations, but also in terms of their possible resilience or vulnerability to environmental stressors, prolonged isolation in small groups, and their interpersonal adaptive skills in groups of mixed gender, culture, ethnicity, occupation, and authority. Examiners must consider whether persons are self-sufficient or seem to require high personal maintenance from associates and authorities.

Because astronauts may undergo expensive training and service status for many years before actually flying in space, hereditary factors must also be considered in terms of expected future mental health. Some of these psychiatric and psychological factors go well beyond the usual definition of relative mental health: simultaneous success in work, personal relationships, and creativity, with the capacity to handle conflicts between instincts, conscience, important other people, and reality with maturity and flexibility (21, p. 127).

High standards of mental health for space crewmembers may seem intuitive, but are difficult to apply fairly and within legal and ethical limits. Although evidence-based standards would be ideal, clinical psychiatric literature, which usually concerns mentally ill individuals, seldom provides explicit data applicable to the early and subclinical conditions that space crew examiners must consider. NASA criteria generally follow the diagnostic formulations of *DSM-IV* (7), adding specific considerations for "traits" and subclinical manifestations. These criteria have been developed through a series of NASA-sponsored interdisciplinary meetings of operational flight surgeons, astronaut flight surgeons, aeromedical and clinical psychiatrists and psychologists, epidemiologists, and psychological testing experts.

During the selection process, psychological tests normed for the astronaut population add some objective data to the interviews, and all decisions are peer reviewed for possible individual bias. As with aircrew, anxiety disorders, mood disorders, and undesirable personality traits are the most common reasons for disqualification (22). Those responsible for developing and justifying selection and retention criteria have studied space-analogous circumstances such as Antarctic overwinter stays, nuclear submarine cruises, survival situations, and historic expeditions (6).

The subject of space crew mental fitness and collective interactions has been examined in the literature mainly, although crew questionnaires obtained before and after missions [for a summary of these data, see Kanas and Caldwell (23)]. Policies of the various space agencies, small size of space crew populations, intense public scrutiny, and difficulty in maintaining individual anonymity make case reports difficult. Still, with continued attention to the subject, and especially with the development of private individual onboard computerized questionnaires, data should accumulate over the next few years. As mission lengths increase and crews become even more heterogeneous, such data will be essential to mission safety and effectiveness and to the mental health of individual crewmembers.

Selection involves predictions of continuing health and especially of mental health, and is a difficult business indeed. Any system of aeromedical selection and certification depends not only on the examiners and the formal criteria, but also on the intelligence, insight, and integrity of the fliers to be forthcoming about medical matters, and to recognize and acknowledge when they are not fit to fly.

MENTAL HEALTH STANDARDS, MAINTENANCE, AND WAIVERS

Formal mental health standards for aviators vary with the type of aviation involved and the certifying authority. In general, the most rigorous standards apply to civil air transport pilots who may command airliners carrying hundreds of passengers, to astronauts and cosmonauts, and to military pilots chosen to fly high-performance aircraft for a career of 20 years or more and who may have access to weapons of mass destruction. The variability of mental health standards makes it difficult to discuss them in more than general terms, and examiners must familiarize themselves with whatever regulations apply to the fliers they evaluate. Aeromedical practitioners should maintain a reasonable level of awareness of mental disorders (clinical suspicion) and request competent consultation when they suspect that pilots have mental health problems. Zimmerman's brief but excellent book lists specific questions useful to the nonpsychiatrist in identifying specific psychiatric disorders (24). A brief clinical assessment may help the aeromedical practitioner to reach primary conclusions about the mental health of an applicant and to decide if further consultation is necessary. Personality disorders may pose a particular challenge (18).

The section that follows briefly presents the major categories of mental disorders and considers their aeromedical implications. The reader is referred to *DSM-IV* (7) and to current psychiatric texts for detailed information about specific mental disorders. Any psychiatric disorder that the aeromedical examiner feels may degrade aviation safety should be cause for deferral of a medical certificate, subject to review by higher aeromedical authorities.

Specific Mental Disorders

Psychotic Disorders

Psychotic disorders involve gross impairment of the ability to perceive reality. A psychotic person may create a personal interpretation of the surrounding world even in the face of contrary evidence that would persuade a nonpsychotic person. Such disorders characteristically involve delusions (firmly held false beliefs about real situations), hallucinations (false sensory perceptions), illusions (misinterpretation of real sensory stimuli), depersonalization (loss of perception of one's own reality), loose associations (illogically connected ideas), or disorganized, bizarre behavior or speech.

All present or previous psychotic disorders should disqualify a person from being an aviator. Waivers or special issuances may be granted when the cause is unequivocally identified as one that was temporary, has ceased, and should never recur (e.g., a past dementia due to toxins, infections, or metabolic problems). Rarely, a mentally healthy aviator undergoing an intensely stressful situation will experience a brief reactive psychosis that clears completely and thereby meets criteria for possible waiver. Positive identification of the cause, along with sound psychiatric treatment, full recovery, and a carefully observed period of subsequent psychiatric normality may allow for consideration of return to flying. Aeromedical judgments in such cases should be conservative, regardless of how sympathetic one is to the desire of the flier to fly again.

Bipolar Affective Disorders

Bipolar affective disorders (BADs), formerly known as *manic depressive disorders*, may take several forms. Psychotic manic episodes are likely to recur despite medication, and so should lead to permanent disqualification. Nonpsychotic BADs have a high recurrence rate and may progress to include psychotic episodes, and so most regulatory authorities regard BAD as intrinsically disqualifying for fliers. Both psychotic and nonpsychotic BAD may respond to medications such as lithium carbonate, anticonvulsants, and mood stabilizers that are themselves a basis for disqualification. Current clinical psychiatric practice includes long-term prophylactic use of such medications after a manic or depressive BAD episode has cleared. This practice leads to difficult choices between leaving such asymptomatic fliers grounded on medication or discontinuing the medication to return the fliers to the cockpit, thereby exposing them to increased risk of recurrence and possible drug resistance. If a flier with a nonpsychotic BAD is considered for waiver, the flier, treating psychiatrist, and aeromedical practitioner should jointly make careful and informed decisions. A company physician may be consulted if the flier is a professional pilot. The certifying authority must approve any decision to return the aviator to flying.

Depressive Disorders

Depressive disorders may present with somatic or emotional symptoms, or with both. Because aviators tend by nature to pay less attention to their internal emotional climate and more to their physical symptoms, they are likely to complain primarily about the way they feel physically, rather than about emotional distress. Somatic symptoms include changes in sleep patterns such as difficulty falling asleep, difficulty staying asleep, restless sleep leading to early morning fatigue, or too much sleeping (hypersomnia). Appetite may increase or decrease, perhaps with weight change, constipation, or diarrhea. The flier may complain of loss of usual concentration and memory, and of headaches or other minor but annoying aches and pains. Emotional symptoms include apathetic loss of interest in usual activities, anhedonia (loss of joy in life), visible slowing (psychomotor retardation) or agitation, distraction, and indecision. The mood may be depressed most of the time, with inappropriate tearfulness, feelings of worthlessness or undeserved guilt, self-reproach, desire to flee from life situations, or death-related ideas that may represent abstract suicidal ideation or may be frankly self-destructive, even including a specific plan (25).

Few aeromedical practitioners would miss the diagnosis if the flier listed the symptoms as openly as given in preceding text, but some of these signs and symptoms may develop slowly over several weeks or months and not be as clear. Some physicians identify so closely with "their" fliers that they do not wish to label a disorder as "depression," perhaps fearing that they will stigmatize a flier to whom they give a psychiatric diagnosis. Some mental health professionals enter into this state of affairs, even in formal consultation, minimizing the symptoms of depressive disorders as being due to external circumstances. Incorrect lesser diagnoses may be given, at times with the stated aim of "not hurting the pilot's flying career," or "not taking away the only pleasure left, flying." Although this is unfortunate from the ethical point of view, it may have other and more serious consequences. Neither the formal literature nor insurance companies recognize flying as a safe or effective form of psychotherapy. An underdiagnosed disorder also may be undertreated. If a major depression is termed an *adjustment disorder*, appropriate medications may not be used. Use of antianxiety medications to treat depression may make the depression worse. Self-medication with alcohol may compromise both flying safety and the pilot's health.

A therapeutic course of any antidepressant medication disqualifies an aviator from flying until the condition requiring its use has been alleviated, the medication and its active metabolites have been cleared from the body (approximately five times the biologic half-life of the medication and its psychoactive metabolites), and the flier has remained off medications and symptom-free for 6 months. Proper selection and use of antidepressant medications is a changing field of study, and aeromedical practitioners should follow the literature. Whatever medication is prescribed for a patient must be used properly, with a careful consideration of target symptoms, therapeutic goals, adequate doses, side effects, drug interactions, and previously agreed-upon indications for completion and discontinuation of treatment.

At this time the presence of depressive disorders requiring current use of medications is disqualifying for medical certification, as is the actual use of psychoactive medications—either the diagnosis or the treatment is disqualifying. Depressions are treatable disorders, and a flier who has been treated, has recovered, has been tapered off medications, and has been symptom-free off medications for approximately 6 months may resume flight privileges with proper authorization. In the United States, the regulations of the Federal Aviation Administration (FAA), NASA, and the three armed services forbid aircrew to fly while taking psychoactive medications. Aeromedical practitioners who knowingly or tacitly allow fliers to fly on such medications do so at their own risk, ethically and legally. These physicians, who overidentify with their depressed fliers, should avoid sympathetic but misguided underdiagnosis and undertreatment. Aeromedical practitioners should also follow the aeromedical literature on this dynamic issue because some modification of official policies may occur in the future (see the discussion of **Psychoactive Medications** later).

Depressive disorders that do not require treatment with medication may not be disqualifying, depending on the nature and intensity of symptoms, the reaction of the flier, and his or her insight into the condition. Experienced examiners or flight surgeons should individually evaluate such aviators in consultation with mental health consultants.

Substance Abuse and Dependence

Substance abuse and dependence are grounds for disqualification. Medical and administrative policies vary considerably in this complex field. In general, examiners who deal with such patients should base decisions on objective evidence rather than on the unsupported word of drug or alcohol abusers. Aeromedical practitioners must be careful to identify persons with personality disorders among those who abuse alcohol or drugs because personality disorders are themselves a reason for disqualification (Chapter 11 discusses rehabilitation programs for substance abusers).

Neuroses

According to classic psychoanalytic theory, neuroses represent unconscious anxiety expressed through symptoms that allow the person to assuage the anxiety indirectly and symbolically. The technologic advances that have supported biologically based psychiatry, and the use of the scientific method to test etiologic hypotheses, allow for some alternative explanations that involve the neurochemistry of anatomic pathways. Genetic studies hold some promise for future prognostic accuracy because the fact that medications relieve such disorders suggests the role of biochemical or metabolic factors.

The current American Psychiatric Association nomenclature has eliminated the classic term *neurosis* and has dispersed its diagnoses among four headings: Mood Disorders, Anxiety Disorders, Somatoform Disorders, and Dissociative Disorders (7, pp. 20–21). The "neurotic" forms of mood disorders include some clinical depressions, as discussed in preceding text. Anxiety disorders include phobias, panic attacks, obsessive–compulsive disorder, acute and posttraumatic stress disorders (PTSDs), and generalized anxiety disorder. Somatoform disorders include hysterical or conversion disorders, hypochondriasis, and some pain disorders. Dissociative disorders include dissociative identity disorder (multiple personalities), fugue, amnesia, and similar conditions. All of these disorders should disqualify the flier, although a few exceptions may be granted depending on the nature and severity of symptoms.

Mental Symptoms due to a General Medical Condition

Mental symptoms due to a general medical condition is the current expression for a condition formerly termed an *organic mental disorder*. This category of disorder distinguishes mental disorders caused by underlying medical conditions from mental disorders induced by external substances and mental disorders that have no specified cause. The underlying medical diseases generally lead to permanent disqualification unless they are reversible and not likely to occur again (e.g., delirium or dementia from acute metabolic or infectious processes).

Adjustment Disorders

Adjustment disorders may require temporary disqualification until the conditions resolve. *DSM-IV* (7, pp. 623–624) names discrete adjustment disorders with anxious mood, with depressed mood, with disturbance of conduct, with physical complaints, with withdrawal, with work inhibition, and with mixed features. Adjustment disorders occur within 3 months of an identifiable external stressor that may be single, multiple, or recurrent, and may be intermittent or continuous. Stressors may be associated with the marital or the parental family, with flying, with social relationships, with job relationships, with physical illnesses, or with religious, legal, financial, or similar concerns. The severity of the disorder may be disproportionate to the severity of the stressor because personal vulnerabilities and other current stressors may vary as well. Therefore, a stressor that barely affects one person may disable another. In an adjustment disorder, counterproductive or maladaptive emotions or behaviors impair function in occupational, scholastic, social, or personal relationships beyond the normal or expected response to the stressor. Symptoms should abate within 6 months of the stressor or its consequences have subsided. If the stressor continues, the disorder may end when the person attains a more effective and less symptomatic level of adaptation.

The ability to handle an aircraft well under difficult conditions of flight does not necessarily indicate an equal ability to deal with all life stressors. Although successful fliers must be able to deal with the specific stressors of flight, this ability does not make them uniquely able to deal with stressors arising from family, interpersonal, or job situations. Marital or relational stressors are the most common sources of difficulty for fliers, followed by interpersonal job-related stressors and career stressors. The afflicted fliers may not be aware of the connection between their stressors and their symptoms.

Adjustment disorders are unique to an individual's present situation, rather than being part of a lifelong pattern that would indicate a personality disorder. If symptoms last longer than 6 months, the diagnosis must be reclassified (e.g., as a depressive disorder). Adjustment disorders associated with substance abuse or dependence must be primarily considered under regulations or administrative procedures concerned with that abuse or dependence, rather than with the adjustment disorder (see Chapter 11). The clinical experience of veteran aeromedical practitioners confirms the wisdom of this policy.

Fliers with adjustment disorders may experience nonproductive, persistent fretting about some problem, thinking about distressing things while flying (daydreaming), or obsessively worrying and becoming distracted in the cockpit. They may lose their usual sense of humor (one of the best coping skills). They may become irritable, have outbursts of anger, use more alcohol, or engage in uncharacteristically reckless behavior. Their upsetting thoughts may lead to a sleep disturbance, to feelings of being trapped by the problem, to preoccupation with otherwise minor physical complaints, and even to an FoF, overt or barely disguised.

These symptoms combine elements of depression, anxiety, and behavioral "acting-out" of distress. Some may be accentuations of a specific flier's usual personality traits, whereas others may represent a considerable departure from the flier's norm. When stressors cause such symptoms in a flier who is basically mentally healthy, the genesis of the problem must be clarified. A brief course of medications may be helpful in alleviating acute distress, but such medications will preclude flying. Counseling or formal "talk therapy" may provide insight into the nature of the problem and how better to cope with it. Once fliers understand where their problems lie, most are willing and adept at doing something about them, and aeromedically oriented mental health therapists find such fliers to be motivated, responsive patients. The fliers may require medications for acute symptom relief, but such medications may be discontinued as the pilots improve their life situations, and therefore time lost from flying is usually minimal.

Personality Disorders and Traits

Personality disorders may be particularly worrisome because their resultant behaviors in aircrew may require administrative as well as aeromedical action. Any flier whose personality disorder manifests itself through repeated overt acts should receive mandatory medical disqualification. Personality itself (temperament) represents an individual's conscious and unconscious behavioral patterns and tendencies—the distinctive way he or she behaves in the environment. An individual's personality derives from genetic, biologic, autonomic, and physiologic attributes, shaped by environmental influences as they are registered, interpreted, stored, and integrated by the central nervous system. Although personality patterns seem to be inborn, childhood influences help develop the brain itself and are therefore crucial to the developing personality.

Personality traits are pervasive patterns of feeling, thinking, and behaving that may be appropriate (not distressing to self or others) under most conditions. *DSM-IV* states, "Only when personality traits are inflexible and maladaptive and cause either significant functional impairment or subjective distress do they constitute Personality Disorders" (7, p. 630). Many people have a few such traits that do not reach the degree of presence or intensity that make them clinically significant (i.e., true disorders). Reactions to environmental or (particularly) interpersonal stress may temporarily accentuate these traits so that they resemble personality disorders, rather than adjustment disorders. Careful history of the time course of the symptoms will allow an accurate diagnosis. *DSM-IV* describes the diagnostic criteria for ten personality disorders (7, pp. 629–673): paranoid, schizoid, and schizotypal (cluster A); antisocial, borderline histrionic, and narcissistic (cluster B); and avoidant, dependent, and obsessive-compulsive (cluster C). Each has a series of defining symptoms presented in a manner similar to those paraphrased here for antisocial personality disorder.

The diagnosis of antisocial personality disorder (older than 15 years) derives from a pervasive pattern of disregard for and violation of the rights of others, as indicated by at least three of the following (7) (p. 649):

- Would not conform to social norms; commits repeated antisocial or illegal acts
- Deceitful: lies, cheats, cons, uses aliases
- Fails to plan ahead; is impulsive
- Is irritable and aggressive; gets involved in physical fights or assaults
- Is reckless concerning safety of self or others
- Is irresponsible; does not sustain consistent work or finances
- Has no remorse or concern about hurting or stealing from others

If a pilot has a personality disorder, it is likely to be antisocial, narcissistic, obsessive-compulsive, or paranoid. Making aeromedical decisions about the fitness to fly of persons with personality disorders may be so difficult as to be almost pathognomonic. The following pointers may help in the process.

Medical authorities should endeavor to base a diagnosis of aeromedically significant personality disorder on solid documentation, whether from the aviation *milieu* or the flier's outside life. This may be the only way to document or assess the "overt acts" referred to in Federal Air Regulation 67 (26). Psychological tests may be helpful, but are usually not definitive (i.e., they are more sensitive than specific). Formal interpretation of the tests must be normed against aviators, not the general public.

When the flier offers complex sets of explanations for a series of improbable life events that have led to medical evaluation, consider a personality disorder as a possible underlying etiology. This diagnosis is especially likely if the flier appears to be one of the nicest people one has ever met, yet claims to be unjustly accused of several somewhat unlikely misdeeds. The aviator may be inappropriately antagonistic or even litigious about an unwanted decision.

Treatment of personality disorders is difficult, if not impossible. The aviator may not have experienced any distress, and may even be proud of his or her behavior, therefore seeing no particular need to change. The flier sees the problem as due to others, not to self, and expects the others to change. If the condition is mild (traits), reduction of life stressors and the acquisition of some insight may alleviate the problem, at least in the aviation context. If the condition is serious, then the mental health consultant, the aeromedical authorities, and the appropriate administrative body should collaborate in making the decision. Consultants and aeromedical practitioners must be familiar with the applicable regulations and aeromedical decision factors.

It may be useful to point out to the aviator that if a medical cause is not found, the offending acts may lead to administrative termination from aviation-related activities by an employer or by the FAA. Quite possibly the flier may be uncooperative, feeling that any medical diagnosis will be undesirable. Such a question as, "Do you realize that if we find you medically qualified to fly, you'll be fired (or decertified) for what you did?" may make the aeromedical practitioner's job a bit easier by enlisting the cooperation of the flier in gathering specific information about the events in question.

Whether encountered in the setting of the military, in airlines, in corporate flying, or in general aviation, such problems are usually so complex as to make their way up to higher levels of decision than the office-level flight surgeon or aviation medical examiner. The most difficult issue may be whether the decision itself is basically medical (which may entitle the flier to sick leave, treatment, disability benefits, etc.) or administrative (which may involve disciplinary or even legal action, or loss of employment) (18,27). One should remember the basic issue, "Is this pilot safe to fly?" If the behavior pattern in question could affect flight safety, the individual should not fly, regardless of whether the problem is defined as medical or administrative in nature. For example, the nature of the overt acts that led to the evaluation may demonstrate an ongoing lack of respect for authority, which would certainly be significant in the regulated world of aviation. If these aeromedically significant acts stem from a personality disorder, the disorder should be the basis for medical decertification until successfully treated. The difficulty of successfully treating some personality disorders is well known. Should treatment be competently accomplished and objectively documented, the recertification process may be initiated.

Maintenance of Mental Health (Mental Hygiene)

General aeromedical concerns include maintenance of health, with particular interest in any disorders that fliers acquire after their selection that could degrade their abilities to function safely or effectively as aircrew members. When such disorders are diagnosed, military fliers are grounded by the proper authority, and civilian pilots may ground themselves or be grounded by the FAA or by their commercial employers.

When one considers how such general aeromedical requirements apply to conditions involving mental health, several new elements appear. "Mental health" is relative rather than absolute. "The best indices of mental health are simultaneous success at working, loving and creating, with the capacity for mature and flexible resolution of conflicts between instincts, conscience, important other people, and reality" (21) (p. 127). Mental health therefore involves such unmeasurable factors as personal happiness, the ability to function in many areas of life, and the effect of one person's actions on others (both close associates and society in general). Some of these factors have an obvious bearing on fitness to fly (suicidal ideas), but others are more difficult to assess (explosive temper).

As with medical conditions, psychiatric symptoms may be aeromedically significant before they are clinically significant. For example, a pilot may be distracted in the cockpit by a family problem, thereby not attending to a change in a cockpit instrument or otherwise not attending to flying conditions. Although these symptoms may not reach the level of a clinical adjustment or anxiety disorder, they may diminish situational awareness and performance, thereby degrading flight safety.

One might reasonably expect the flier to recognize the occurrence or recurrence of distressing somatic symptoms. However, some mental conditions affect introspection, insight, judgment, or cognitive function, so self-report may not be entirely dependable, even in pilots of the highest character. This aspect of mental illness mandates disqualification of any pilot with BAD or with a psychotic disorder.

Fliers may receive secondary gain from symptoms. In classic psychiatric terms, the primary gain of psychological defense mechanisms is to provide relief from internal conflicts and their attendant anxiety. The secondary gain is that the symptoms may attract "personal attention and service, monetary gains, disability benefits, and release from unpleasant responsibilities" (21) (pp. 166, 188). For example, a male pilot might receive compensation for his phobic FoF for several years. Free of distress in his daily life, he works at another job. He does not pursue psychotherapy for his FoF because he feels well. If he has to return to the cockpit his fears are activated, his symptoms recur, and he becomes disabled once more because of (a) having to return to flying (negating the primary gain from his symptoms) and (b) losing his disability pay (negating the secondary gain). Treatment of such a complex interaction of psychiatric and occupational factors requires more than just prescribing medication. A cognitive-behavioral or psychodynamic approach (talk therapy) may be effective if the flier is willing to form a therapeutic alliance with a therapist, but is unlikely to succeed if the flier does not wish to participate and cooperate in the effort to return to flying activities.

Waiving Psychiatric Disqualification for Flying

An individual aviator who has had a mental disorder may receive a waiver or special issuance as an exception to general mental health standards. This process may be undertaken when that flier's mental disorder is no longer present, or has subsided so that it does not endanger either the flying safety or the effectiveness of the flier, and is unlikely to recur.

Although many fliers believe that any psychiatric disorder will end their flying days, most such disorders are waived; 65% of U.S. Air Force fliers hospitalized for psychiatric disorders were returned to flying status (RTFS) within 2 years, and the proportion of fliers RTFS among those with psychiatric disorders who were not hospitalized was even greater (28). Even self-destructive actions do not mandate the end of a flying career; aeromedical authorities ultimately returned to their cockpits 11 of 14 fliers (79%) referred for aeromedical consultation after the successful treatment of the conditions leading to their suicide attempts (29).

Decision Criteria for Waivers

Waiving mental health disorders in an individual flier requires a more detailed and extensive history than that usually given in a "regular" clinical psychiatry consultation, as well as psychological testing with aeromedically sophisticated interpretation. The aeromedical practitioner must judge the certainty of the mental health diagnosis, its probable future course, the options for prophylaxis, the dependability of the flier's judgment and insight, and the chance of recurrences. Statistical data about the condition must also be analyzed to extract the kind of information necessary for aeromedical decision making. Family information must be considered, including the level of personal support and dependable observation. The quality and availability of personal medical and mental health care is also important. Evaluation of the flier's flying *milieu* must include not only routine flying conditions, but also worst-case scenarios involving emergencies, multiple operational stressors, and various personal and situational factors. Clearly, all these factors bear on a given case and no set or standard answer is possible. It is simple to say, "You will never fly again." It is much more difficult to say, "Here is how we know that it is now safe for you to fly." What criteria allow the aeromedical practitioner to recommend return to flying duty in a particular case?

Reevaluation of such waivers should include considerations of the periodicity of routine physical examinations, the nature of the disorder, the flier's capacity for accurate self-appraisal and honest action, and the availability of everyday observation from family members and fellow fliers. Most certifying authorities have policies to help determine such matters. To be aeromedically waiverable, the following medical conditions must (30):

- Pose no risk of sudden incapacitation
- Pose minimal potential for subtle performance decrement, particularly with regard to the higher senses
- Be resolved or be stable, and be expected to remain so under the stresses of the aviation environment
- Have easily detectable initial signs or symptoms if the possibility of progression or recurrence exists and not pose a risk to the individual or the safety of others
- Require no exotic tests, regular invasive procedures, or frequent absences to monitor for stability or progression
- Be compatible with the performance of sustained flying operations in austere environments

The last of these criteria, which apply to military situations, may not apply to other aviation settings. Certifying authorities should judge mental health conditions using these or somewhat less strict criteria appropriate to the type of flying involved.

LIFE STRESS AND FLYING STRESS

Once selected, fliers face not only the stressors of aviation, but also those of everyday life. A flying career does not protect a person from acute stress reactions, psychophysiologic disorders, or depression. The coping skills that allow a pilot to deal effectively with inflight emergencies are not the same as those required to deal with family or occupational pressures. Aerospace mental health issues exceed the usual clinical concepts of normality. The aeromedical practitioner must be prepared to recognize and manage mental health disturbances at the preclinical level where they may detract from flying performance, but may not yet have reached the magnitude of clinically diagnosable disorders. Not all mentally healthy ("normal") people can fly safely or effectively. Likewise, not all persons with past or present mental health problems are necessarily unsafe or ineffective fliers, hence the existence of waivers. These paradoxic statements arise in part because some people react quite differently to aviation stressors than they do to life stressors. Because aircrew errors are a major source of aircraft accidents, mental health concerns in aeromedical practice must include safety concerns, especially because any "pilot error" involves mental (psychological) factors in some way.

Aeromedical practitioners should remain alert for clinical disorders of mental health, and additionally for subclinical symptoms that may affect flying safety or effectiveness. These include symptoms of overstress, anxiety, or depression. Examples include the following:

- Increased mistakes in the cockpit or in everyday activities
- Distraction by worries or nonproductive, persistent obsession about some problem, especially while flying
- Loss of usual sense of humor (one of the best coping skills)
- Uncharacteristically reckless behavior
- Emotional distress and easy tearfulness
- Mood changes, particularly increased irritability or inappropriate anger
- Repeated arguments without closure
- Hopeless feelings; feelings of being trapped by a problem
- Inability to feel happy (anhedonia)
- Disturbed sleep, possibly linked to repetitive thoughts
- Recent onset of barely disguised or overt FoF
- Unexplained weight change
- Diminished interest in sex (libido)
- Inappropriate concern about somatic symptoms; preoccupation with otherwise minor physical complaints
- Increased use of alcohol or sleeping medications

Military flight surgeons who have easy medical access to their fliers may be able to take some measures that are more difficult for civilian examiners. Such measures include the following:

- Educating fliers about life and aviation stressors; discuss some of the ways that stress-related symptoms appear and what to do about them; continue with discussion of manifestations of life stressors in the aviation arena
- Learning to identify the stressed aviator; teaching supervisors and peers to be alert to such signs and symptoms
- Making appropriate therapeutic recommendations when needed
- Grounding the aviator when necessary, until stressors are past or until the aviator learns better ways of coping

FEAR OF FLYING

Fear of flying is an aeromedical term for a symptom that may arise from many life circumstances. The psychiatric literature does not use this term, although the aeromedical literature has long discussed FoF as if it were a distinct entity. It may be a manifestation of several mental health disorders (31). The only mention of FoF in *DSM-IV* (7, pp. 405 ff) refers to overt and long-standing "specific phobias" that occur in a small proportion of aircraft passengers; this almost by definition occurs in people who are not aviators.

FoF in fliers signals a serial change in their motivation and adaptation. When experienced aviators who previously enjoyed flying become afraid to fly, it may represent a complex mix of acute or chronic causes and symptom presentations. In such fearful fliers, anxiety about symbolic threats may overlay a rational fear of actual risks; this may represent a reaction to a near or actual accident, or displaced anxiety from a personal crisis, or a loss of motivation to fly that threatens the flier's self-esteem as a competent and powerful person.

Whatever its genesis and presentation, symptomatic FoF should medically disqualify any aviator from active flying until the causes are delineated and the underlying disorder has been successfully treated. Such treatment may involve meticulous psychiatric history taking and some psychodynamic exploration, as well as brief pharmacotherapy and behavioral modification techniques (8,31,32).

Postmishap Disorders

First, and most obviously, a flier may develop an acute adjustment or PTSD (7, pp. 424 ff) after a flight-related event or mishap. The acute fear may at first be denied or suppressed, but finally overcomes the flier's defenses and becomes clinically evident. The flier or the physician may easily relate the onset of symptoms to the mishap. The symptom complex may meet the formal diagnostic criteria for an acute adjustment disorder and may progress to PTSD. Because treatment of PTSD is lengthy and difficult, the flier should receive preventive measures and early intervention after any significant mishap. These include a routine discussion of his or her emotional reaction to the mishap, acceptance of the usual initial denial of any negative feelings, reassurance that some bad feelings are normal, and a brief explanation of phenomena such as nightmares, flashbacks, aversions, anxiety, and emotional numbing. The flier's original and current motivation to fly should be discussed, and the entire matter left open for future discussion. This approach has long been a feature of the aeromedical literature and its principles closely resemble the more formal crisis intervention techniques now used in civil and military disaster situations (33). Current psychiatric research indicates a neurochemical basis for PTSD, and aeromedical practitioners should be alert for possible future recommendations for use of a prophylactic medication within a few hours of an acute traumatic event.

Phobic Disorders

Phobic FoF may occur without an obvious antecedent event in a previously unafraid aviator. It may begin insidiously and then worsen in an aviator who has previously enjoyed flying. The flier may be mystified by unpleasant anxieties that may start as exaggerated fear of a specific aviation setting already known to be challenging (e.g., bad weather, night flying) and then extend into other facets of flying. These symptoms are distasteful to the flier (egodystonic) and are usually because of some problem outside of flying, such as burdensome domestic, financial, or life decisions. Because the feared flying situation actually represents displacement onto aviation of anxiety about the underlying life dilemma, the symptoms are disproportionate to the actual aviation setting and the flier may become obsessed by them; for example, checking and rechecking weather reports or attempting to avoid flying at night. Therefore, careful history concerning life situations just before the onset of symptoms is crucial to diagnostic formulation and to treatment.

Treatment of flight phobia may consist of a combination of behavioral modification (relaxation and desensitization) with cognitive or insight-oriented talk therapy to identify and deal with the life problem, preferably with an aviation-oriented therapist. A few trial flights with another pilot may help demonstrate improved adaptation to flying. Most aviators respond well to this approach because of the egodystonicity of the symptoms and the economic incentive to return to flying, and may resume cockpit duties once their anxiety is allayed. Treatment may include the use of medications only in the initial stage because medications are incompatible with aviation duties.

Somatoform Disorders

Somatoform disorders or symptoms represent difficult forms of FoF. These are chronic physical or physiologic symptoms, presented by a professional aviator (sometimes preceded by the words, "I'd like to fly, but . . .") as incompatible with continuing to fly. This presents a striking contrast to the usual attitude of most fliers that they can fly in spite of their symptoms. A reluctant flier's symptoms arise from an unconscious conflict between anxiety about flying and a greater anxiety about giving up the role of the aviator. "Involuntary" grounding for physical reasons beyond the flier's conscious control offers an acceptable way out of the conflict. Existing life stressors may accentuate the symptoms. The aviator has no conscious anxiety about flying, and therefore responds to any question concerning apprehension in flight with angry denial because the question represents a challenge to the defense that the symptoms offer against the intolerable but unconscious underlying anxiety. The flier may have little concern about any disease that the symptoms might represent, concentrating instead on being removed from flying duties in order to avoid the distress. The entire presentation case differs from that of the usual aviator who does not want to be grounded. The frustration and irritation of both pilot and physician in dealing with symptoms that are out of proportion to the medical situation may indicate the psychological secondary gain involved.

Three clinical observations may help identify the unconscious aspect of the symptoms. First, the flier tends to describe the symptoms in terms of their effect on flying. Second, the flier may express no particular anxiety about being significantly ill, and have little interest in specific treatment. Third, if asked, "Will you go back to flying when you are well?" the flier may equivocate or signal reluctance. Identifying the somatoform nature of the problem may allow the physician to avoid unnecessary, expensive, or invasive diagnostic procedures. Even if the psychologic nature of the problem is established, the flier is unlikely to agree with the formulation and to cooperate in necessary psychotherapy. The nature of the symptoms (headaches, various pains, sensory deficits, autonomic disturbances of the gastrointestinal tract) may preclude safe return to flying duties. Once firmly established, somatic presentations of FoF may be quite resistant to therapy (8).

Psychophysiologic Reactions

Hyperventilation and syncope, two acute psychophysiologic reactions with aeromedical implications, may occur because of anxiety. Neither is listed in *DSM-IV* as constituting psychopathology, except for vasovagal fainting responses to injections (7, p. 407), and either reaction may occur in response to physical, situational, or social stressors without the presence of a disease of any kind. Cardiovascular and neurologic disorders must be carefully ruled out, but many episodes of inflight hyperventilation or of ground-based syncope occur in healthy individuals. An episode of spatial disorientation or of hyperventilation in flight may trigger intense symptoms of anxiety. Loss of motivation to fly may undermine previously adequate means of coping with the true dangers of flight, particularly in professional aviators. Interpersonal conflicts with significant individuals in a nonaviation setting (home, office) may precipitate aviation-related anxiety without any obvious connection to flying except the time of onset.

Hyperventilation in fliers may present as an inflight physiologic incident that must be differentiated from hypoxia or exposure to toxic fumes. Once these possible external etiologic elements are eliminated, the physician must rule out any physical reason (cardiac, metabolic, and neurologic) for the symptoms. When spontaneous hyperventilation has been diagnosed, then the physician must establish the reason for the hyperventilation. This usually involves acute or chronic anxiety, or both. Treatment should take into account any underlying situational anxiety such as family pressures, and the more pressing problem of how the flier may deal with the realistic fear that the dangerous symptom may recur. An effective means of addressing incipient hyperventilation is for the flier to control respiratory depth and rate by breathing through the nostrils, which act as flow-limiting valves. Counting the number of seconds of each inhalation and exhaling for twice that count will control the rate. If the inhalation takes 2 seconds, the exhalation should last 4 seconds (a 6-second cycle, or a respiratory rate of 10 breaths per minute). Brief practice will demonstrate that hyperventilation is impossible when this technique is followed, and the flier will be reassured that he or she has an effective counter to any future episodes. This reassurance, plus an inflight demonstration if possible, reestablishes the flier's sense of self-control in the cockpit.

Psychogenic syncope may result from loss of sense of control (e.g., spatial disorientation), threats to bodily integrity (e.g., venipuncture, or restraining a child being sutured), and upsetting social situations. The threat may even be implied, as when a flier witnesses a graphic first aid movie. The author has consulted with healthy aviators who have fainted in settings of acute embarrassed anger (male fliers being berated in public by a superior officer where no response was allowed, female fliers responding to subtle unwanted sexual advances) and cultural pressure (continuing to stand at attention at a military ceremony after a long day's flight, no food and several drinks, despite clear premonitory symptoms of postural hypotension). Such events have the common element of the aviator having to remain passive in the face of a perceived threat, and therefore almost never occur in the cockpit where active response is the norm.

Prevention involves teaching fliers to recognize and heed the early warning symptoms of lightheadedness, altered awareness of surroundings, constricted or dim vision, weakness, tingling, and any additional symptoms of orthostasis. Should they recognize the prodrome, the necessary action should be to assume whatever position places the head at or below the level of the heart. This might involve lying down in somewhat unusual situations, but remembering, "Lie down; pride goeth before a fall!" may suffice.

SPECIAL TOPICS

Psychoactive Medications

Changes in psychoactive medications are coming so rapidly that a textbook discussion of their aeromedical implications should be general rather than specific to avoid becoming outdated. All aeromedical practitioners should maintain at least a general familiarity with current antidepressant and antianxiety medications. Such medications must be used properly, with a clear eye to target symptoms, therapeutic goals, adequate doses, side effects, drug interactions, and previously agreed-upon indications for completion and discontinuation of treatment. Primary care physicians may not be as careful about these factors with patients who have less serious "adjustment reactions" or "life problems" as they are with patients who have major depressive or anxiety-related disorders. Some physicians may even prescribe such medications solely for symptomatic relief, without ever establishing a formal diagnosis or therapeutic endpoint of any kind.

Considerable aeromedical discussion involves whether a flier might be safely cleared to fly while taking one of the newer antidepressants, particularly the serotonin-specific reuptake inhibitors (SSRIs). A panel of aeromedical psychiatrists and practitioners at the May 1994 Annual Scientific Meeting of the Aerospace Medical Association unanimously agreed that this practice would not be aeromedically indicated for safety reasons. This conservative position is logical and easily understood. However, at least three situations illustrate the problems involved in its inflexibility:

1. Canadian authorities have recently certified six meticulously studied pilots to fly "with or as a copilot" while taking a maintenance dose of individually specified antidepressants: three pilots for chronic depression resistant to drug withdrawal and three for prophylaxis against recurrent depression. These pilots have been carefully followed up for an average of 5 years without incident, representing 30 man-years of experience (M. Lange, *unpublished data* presented at the U.S. Civil Aviation Medical Association meeting, October 2000), and this may represent the future pattern of aeromedical use of selected psychoactive medications. No published peer-reviewed scientific literature currently supports aeromedically oriented research to cite as a precedent, but two recent abstracts indicate that such reports may be forthcoming (34,35).
2. Medical advisors to the Air Line Pilots Association reviewed approximately 2,500 telephone calls from pilots concerning mental health matters between 1993 and 1997. Of these, 1,200 concerned the prescription of medications for depressive symptoms. Approximately 710 (59%) of the pilots said they had not taken prescribed medications because they would have to stop flying. Another 180 (15%) said they would take the medications and not tell the FAA so that they could continue to fly. Only approximately 300 (25%) said they would take sick leave in order to take the medications, understanding that they would be away from flying for approximately 9 months. Therefore, most commercial pilots either chose to fly with their disorders untreated or to fly while taking medication under aeromedically unsupervised and illicit conditions (D.E. Hudson et al., *unpublished data* presented at the U.S. Civil Aviation Medical Association meeting, October 2000). Other pilots may well be making the same choices.
3. Physicians may prescribe bupropion HCl or similar medications for control of withdrawal symptoms in smoking cessation programs; the FAA has not approved aviators to use these medications for this purpose. The psychophysiologic effects of nicotine withdrawal pose their own risks to aviation (36), risks that should be balanced against those involved in using medications to help suppress unpleasant symptoms of withdrawal.

These three illustrations demonstrate the need for reevaluating existing policies and considering possible criteria for granting waivers or special issuances for the use of some antidepressant medications such as SSRIs under controlled conditions. Aeromedical practitioners should follow the aeromedical literature on this dynamic issue because some modification in policies will undoubtedly occur in the future.

Air Transport and Aeromedical Evacuation of Psychiatric Patients

Psychiatric disorders may result in considerable incapacitation, or in disruptive or dangerous behavior. None of these is compatible with routine airline travel. The physician who must decide whether a person with a mental health disorder can fly alone as a passenger must consider not only routine travel conditions but also the chances that a flight may be delayed or even canceled. The patient may be unable to manage transfers between flights in unfamiliar airports, gate changes, lost luggage, cramped and crowded seating, delayed toilet access, and other disruptions. Upset routines, confusing procedures, lack of privacy, and other inconveniences may unduly agitate some psychiatric patients. The evaluating physician should consider such "worst-case" scenarios, and may usefully consult a knowledgeable family member, neighbor, or friend before deciding whether a psychiatric patient can fly alone, with an attendant, or at all (37). If a psychiatric patient is to travel with an attendant companion, the airline may require prior notification.

Careful consideration should be given to medications in such a situation. A psychoactive medication should not be prescribed for travel unless the patient has taken it before, has responded well to it, and has had no undue side effects. An airliner is no place for a patient to suffer an allergic or dystonic reaction, an idiosyncratic response, or a drug–drug interaction.

The physician should also consider whether the anticholinergic properties of some medications might slow digestive processes, leading to excessive intestinal gas formation that might be aggravated by increased volume at altitude (37).

Passengers who are phobic about flying may benefit by premedication with anxiolytic medications. If multiple flights are necessary, one of the airline-sponsored desensitization programs may be of benefit (31).

Aeromedical evacuation of psychiatric patients is a common practice in the military, and experience has shown that proper screening of patients can make this a safe and practical means of transportation. Decisions about the use of psychoactive and sedating medications, litter transport, and restraints should be made conservatively, considering safety of flight and of other patients at all times (38). Such considerations may easily be applied to civilian medical transport situations.

Suicide by Aircraft

Aviators have access to aircraft as an instrument of self-destruction, actions that are unusual but not unknown. A case report of such an occurrence in the early 1970s reviewed the literature to that point (25) and others have been reported since that time. Circumstances vary; some mishaps where self-destruction has been alleged or proved have involved depressed persons who wished to leave their families large insurance settlements. Others have involved religious delusions or instances of anger. Some persons have stolen aircraft and been unable to fly them, and some have involved subintentional self-destructive tendencies, such as one in which the flier flew dangerously and foolishly, daring death in a "Russian roulette" manner. Alcohol or drugs may be involved in such actions.

Because most aircraft suicides involve litigation, it may be difficult to investigate them in civil or general aviation as evenhandedly as in the military, where legal immunity and the absence of liability issues may allow witnesses more latitude. Investigators must distinguish between a death that occurred because of intentional action and one resulting from foolhardiness, inattention, or negligence. Considerations include elusive personal elements: distraction, longing to get home, sensory overload, fatigue, or external sources of stress. Adding external elements such as depression, illness, romantic misadventures, financial strain, or feelings of hopelessness or guilt make matters more difficult. The diagnosis of suicide by aircraft must begin with the recognition that these events do occur, and clinical suspicion should be raised not only by the circumstances of the death, but also by clinically significant recent events in the victim's life. As is true elsewhere in medicine, nothing replaces a good history once clinical interest is aroused. Shneidman's concept of "subintentional suicide" is useful in ambiguous mishaps and the reader is referred to his work for further information on this matter (39).

Aggressive Airline Passengers

Airline passengers who become verbally or physically assaultive in flight pose a potential hazard to flight safety, as well as to the safety of crewmembers and other passengers. U.S. Federal Air Regulations 91.11, 121.580, and 135.120 state that "no person may assault, intimidate, or interfere with a crewmember in the performance of that crewmember's duties aboard an aircraft being operated." Aircrew report 200 to 300 of these incidents each year (http://www.faa.gov/data_statistics/passengers_cargo/unruly_passengers/). In 1999, the United Kingdom Civil Aviation Authority reported that its air carriers estimated the incidence of serious assaults at 1 in 18,000 flights, and the incidence of all assaults (including minor altercations) as 1 in 870 flights. Alcohol contributed to approximately half these incidents, and smoking (including smoking in aircraft toilets) featured in approximately a third (www.aviation.detr.gov.uk/disrupt/990410/index.htm).

Cabin crewmembers, and perhaps cockpit crewmembers, occasionally find themselves involved in verbal and sometimes physical confrontations with passengers. Their management of abusive or assaultive passengers may have medical implications, but is not primarily a medical responsibility. Physicians who are passengers on an aircraft where such incidents occur may be asked to help control the offenders, either verbally or with the use of medications. Although the offender may appear simply to be drunk, differential diagnoses will include mental and physical illnesses with mental manifestations, perhaps complicated by acute alcohol or drug intoxication. The offending passenger may also be taking one or several legitimately prescribed medications.

In his first aphorism concerning the practice of medicine, Hippocrates warned that the occasion could be instantaneous, experiment perilous and decision difficult. Dealing with a large, aggressive, drunken passenger in the limited confines of an airliner meets these criteria. Although this sort of situation has some similarity to confronting intoxicated and potentially dangerous patients in emergency rooms, those settings include a legally recognized medical interaction amid familiar surroundings, supporting staff, medical supplies and equipment, and access to security personnel. An aircraft is a different setting in these and other respects. No clear legal precedents exist concerning authority to act, liability, permission, or lack of informed or implied consent when dealing with a recalcitrant and oppositional individual. The airliner maybe of one nationality, the passenger of a second, and the physician of a third. The aircraft may be flying over one or several countries, or even over international waters.

No explicit medical guidance or peer-reviewed medical citations are currently available for reference. From the psychiatric point of view, the best counsel is to be cautious. Any passenger-physician in such a situation should be aware that the captain may be able to establish a telemedicine link with experienced medical personnel on the ground, and the physician should take advantage of whatever consultation should be available through that modality.

The physician present may have much experience in similar settings or may have none. The physician is also a passenger at risk, may have had a drink or two, and may be as emotionally upset as everyone else. Cabin crew and fellow passengers may have unrealistic expectations, and may urge actions that are medically and medicolegally inadvisable or unwarranted. This may be especially true in considering whether to sedate the offender with onboard medications. As noted in the section on **Aeromedical Evacuation**, one should avoid giving a medication in flight, especially parenterally, that is not known to be safe through experience with its use in the individual on the ground.

The prospect is one of giving powerfully sedating medications and possibly supervising involuntary physical restraint of an antagonistic stranger in a crowded and isolated environment with strictly limited medical resources and minimally trained ancillary personnel. The medical history (including prescribed medications) is unknown, the person is not one's own patient, has not consented to medical services from anyone, and may have consumed an unknown amount of alcohol or illicit drugs.

The scenario outlined before appears to be not a medical situation, but one involving safety and security. In more familiar hospital settings, confrontations with assaultive patients are managed by isolating them, and trying to establish an ambience of calm conversation and reason to defuse the crisis. The physician should use a calm and low voice, avoid profanity and confrontational statements or threats, remain physically relaxed, and perhaps even adopt a "thoughtful" physical stance (one hand on one's cheek and the other arm crossed in front of one's body), but avoid staring at the patient. Signs of increasing agitation include raised voice, physical motion and agitation, clenching and unclenching fists, darting eyes, intrusion into personal space, and physical touching or shoving. When physical restraint proves necessary, an overwhelming, trained, and organized force that ideally includes professional attendants, security, or police personnel should confront the patient. They should accomplish restraint with minimal physical force, taking care to avoid injury if possible. Particular care is necessary when using chokeholds or other maneuvers that may impede not only respiration, but also the blood supply to the brain. The physician may be an onlooker or even an advisor, but may choose not to assume professional responsibility for such proceedings in a nonmedical setting. The aircraft captain, not the physician, is the authority.

In summary, caution, prudence, knowledge of situational and professional limitations, and avoidance of overstepping professional boundaries should guide physicians who find themselves in confrontations with their fellow passengers.

Genetics

Current active research in the genetics of mental disorders may help predict the chances of occurrence or recurrence of some psychiatric disorders. If genetic analysis improves our ability to evaluate individual fliers, waivers or specific exemptions may be granted with greater precision. Because most psychiatric disorders are now diagnosed by their clinical presentations, rather than by objective tests, identifiable biochemical or genetic markers will represent a great improvement in the accuracy of diagnosis and prognosis for fliers with mental health disorders.

MILITARY ISSUES

Deployment and Peacekeeping Missions

Peacekeeping missions require repeated or extended periods in foreign and sometimes unpleasant environments. Reservists or other "part-time warriors" may be particularly susceptible to deployment stressors, including disruption of usual activities, financial burdens, uncertain deployment length, changing plans, waiting, boredom, jet lag, fatigue, poor mail or telephone service, lack of privacy, physical discomfort, unpleasant climate, lack of equipment or supplies, abstract or unclear goals, possible or actual terrorism, and a sense of personal danger on the ground as well as in the air. The flight surgeon may not have the power to correct all the stressors that may affect flying safety and effectiveness, but may reduce some by attending to basic amenities like sleep, water, food, and comfort. The flight surgeon should watch for evidence of poor morale such as poor performance or military bearing, loss of the fliers' usual sense of humor, a rising noneffectiveness rate, increase in alcohol consumption, and minor disciplinary infractions. Unit commanders and flight surgeons should take stress-related misbehavior seriously, and should rapidly investigate such infractions. Judicious use of time off, recreational facilities, educational and sports programs, civic action programs, and the like may help reduce morale problems that could affect flying safety and effectiveness. When the deployment draws to a close, a formal closure such as a banquet, farewell party, or ceremony may reinforce a sense that the mission was accomplished with honor and purpose.

Flight Surgeon Support to Aviators in Combat

Air combat operations add battle stressors to those of deployment. The books by Bond (11) and Grinker and Spiegel (40) are classic basic texts on this subject as observed in World War II fliers. Fliers now tend to be older and better educated, and recent combat operations have been brief and limited, generally flown as sustained operations under conditions of air superiority. However, many factors of aeromedical support to combat operations seem to endure from decade to decade.

Combat operations attempt to break the enemy's will to resist; this includes causing stress-related symptoms among enemy troops while the enemy tries to do the same to friendly troops. Whereas the first medical impulse may be to evacuate symptomatic troops, the essence of leadership and good military medical practice is to return these troops to duties, at least for a while. As with noncombat deployments, flight surgeons should assure that basic amenities are well provided. With the modern emphasis on sustained 24-hour operations, sleeping facilities ought to be quiet and somewhat removed from the flight line, soundproofed and climate controlled for undisturbed rest. Meals should be attractive, nourishing, and available at all hours. Fliers need access to showering facilities and to clean laundry. Attention of base authorities to these services is not only important to the physical comfort of the flier, with its resulting increase in efficient flight, but serves as tangible evidence of the unity with which the base supports the flying mission.

Judged by personal accounts, aerial combat is exhilarating to some participants, but as wearing in its own way as infantry combat. As with ground troops, identification with a competent and professional unit is important in dealing with any personal feelings of doubt or fear in combat. Individual soldiers may believe that "I am the only one who is so frightened," a feeling that contributes to combat fatigue. Frank discussion of fearful feelings by the flight surgeon or the squadron commander help allay the perception of fliers who feel that they alone are experiencing the cognitive and autonomic sensations of fear. The clear message must be that it is normal to be aware of such fear and that the unit accepts it as long as the fliers perform their duties.

Combat fatigue is based in part on true physical fatigue, as well as on the internal struggle between an individual's wish to avoid danger and the wish to face it in order to do one's duty. Therefore, those responsible for scheduling missions should provide time for sleep; 4 hours of uninterrupted sleep per

24 hours is the irreducible minimum for the first few frantic days of combat operations, and then schedules ought to allow for 6 to 8 hours of sleep as soon as possible. Much research is being conducted on sleep hygiene in combat operations, including the use of sedative and stimulant medications, and operational flight surgeons must maintain familiarity with current literature and policies, rather than trying to learn about them once hostilities begin.

Experienced flight surgeons in previous wars generally have concurred with brief 1- or 2-day rest periods for fliers each week or so, with a longer break (off-base rest and recreation) of approximately 9 days every 6 months. Combat tours should be established as soon as possible; these have traditionally been measured either by number of missions or by number of days in action. These and associated subjects have been thoroughly discussed by Jones (41).

There is no ethical way to simulate fear in combat exercises, and fliers may be shocked to recognize their fears in their first few combat sorties. Most fliers will adapt fairly quickly, using defenses they have used before. Because aviators have similar personalities, they tend to use similar defenses: humor, anticipation (planning), suppression, denial, rationalization, intellectualization, and repression (42). Fliers present these elements with exaggerated understatement, bravado, and fatalism in discussions with squadron mates.

Flight surgeons have two main ways to prevent or delay combat-related stress symptoms: rest and personal influence. Billeting the flight surgeon with the fliers guarantees medical interest in the elements of rest already discussed. Personal influence (transference) between flight surgeon and flier is crucial. The flight surgeon must provide excellent medical care; nothing will compensate for professional shortcomings. The flight surgeon will assume a role within the squadron as an authority figure, reinforcing fliers' trust in their own skill, training, and equipment. By sustaining the fliers and also working toward the goals of the unit, flight surgeons help fliers to control their fears by buttressing their coping skills and defenses, rather than by relieving them of their duties. Flight surgeons serve as an informal link in the chain of command, an alternate pathway for getting things done. They should fly as combat observers themselves to establish their credibility, make pertinent aeromedical observations, gain experience useful in dealing with combat stress, and inform commanders about matters concerning combat effectiveness and safety.

When combat fatigue is a concern, flight surgeons should see the squadron members everyday in the flight line environment and talk to fliers before and after missions. Inquiries include sleeping patterns, social withdrawal, irritability, temper outbursts, tremors, and abuse of caffeine, nicotine, and alcohol. Early symptoms of alcohol abuse in the combat setting may include fliers' reports of changing sleep patterns so that they drink in order to get to sleep, or when they or other fliers notice that they are less sharp in the cockpit.

Flight surgeons should suspect secondary gain from symptoms when fliers ask to be grounded, or when grounded fliers seem in no hurry to get back to flying, miss appointments, ask to stay grounded longer, or ask to be assigned to limited duty. Flight surgeons may depend on the wisdom of line officers about what the squadron can do, and of the fliers themselves about when one of them has "paid his/her dues." This may help the flight surgeon to decide whether to be tough or sympathetic about symptoms of fear.

Regardless of the severity of the military situation, a flier who crashes because of stress-related factors contributes nothing. Military flight surgeons who support combat operations share with their civilian colleagues a responsibility to base aeromedical decisions on the keystone of aerospace medicine, flying safety.

REFERENCES

1. Hart C. *The prehistory of flight*. Berkeley: University of California Press, 1984:117.
2. Bach R. *Stranger to the sky*. New York: Dell, 1963:75.
3. Anderson HG. *The medical and surgical aspects of aviation*. London: Oxford University Press, 1919.
4. Armstrong HA. *Principles and practice of aviation medicine*. Baltimore: Williams & Wilkins, 1943:2, 460ff.
5. Magee JG Jr. High flight. *Newsweek* 1942;14:27.
6. Santy PA. *Choosing the right stuff: the psychological selection of astronauts and cosmonauts*. Westport: Praeger, 1994.
7. American Psychiatric Association. *Diagnostic and statistical manual of mental disorders*, 4th ed. Washington, DC: American Psychiatric Association, 1994.
8. Jones DR. Flying and danger, joy and fear. *Aviat Space Environ Med* 1986;57:131–136.
9. Leimann Patt HO. The right and wrong stuff in civil aviation. *Aviat Space Environ Med* 1988;59:955–959.
10. McGlohn SE, King RE, Retzlaff PD, et al. *Psychological characteristics of USAF pilots*. AL/AO-TR-1996-0097. Brooks AFB: USAF Armstrong Laboratory, 1996.
11. Bond DD. *The love and fear of flying*. New York: International Universities Press, 1952.
12. Jones DR, Marsh RW. Psychiatric considerations in military aerospace medicine. *Aviat Space Environ Med* 2001;72:129–135.
13. Beaven CL. *A chronological history of aviation medicine*. Randolph Field: School of Aviation Medicine, 1939.
14. Fine PM, Hartman BO. *Psychiatric strengths and weaknesses of typical air force pilots. SAM Technical Report 68–121*. Brooks Air Force Base: USAF School of Aerospace Medicine, 1968:131–168.
15. Reinhardt RF. The outstanding jet pilot. *Am J Psychiatry* 1970;127:732–735.
16. Christy RL. Personality factors in selection of flight proficiency. *Aviat Space Environ Med* 1975;46:309–311.
17. Helmreich R, Gregovich S, Wilhelm J, et al. Personality based clusters as predictors of aviator attitudes and performances. In: Jensen R, ed. *Proceedings of the fifth symposium on aviation psychology*. Columbus: Ohio State University Press, 1989:607–702.
18. Christen BR, Moore JL. A descriptive analysis of "Not Aeronautically Adaptive" dispositions in the US. Navy. *Aviat Space Environ Med* 1998;69:1071–1075.
19. Merchant PG, Baggett JC. Aerospace Medical Panel. The concept of aeronautical adaptability as developed by the US. Navy. In: ed. *The clinical basis for aeromedical decision making*. AGARD CP-553-6. Neuilly-sur-Seine: NATO Advisory Group for Aerospace Research and Development, 1994:14.1–14.7.
20. Mills JC, Jones DR. The adaptability rating for military aeronautics: a historic perspective of a continuing problem. *Aviat Space Environ Med* 1984;55:558–562.

21. Edgerton JE, Campbell RJ III, eds. *American psychiatric glossary*, 7th ed. Washington, DC: American Psychiatric Press, 1994.
22. Santy PA, Holland AW, Faulk DM. Psychiatric diagnoses in a group of astronaut candidates. *Aviat Space Environ Med* 1991;62:969–973.
23. Kanas N, Caldwell B. Summary of research issues in personal, interpersonal and group dynamics. *Aviat Space Environ Med* 2000;71(Suppl 9):A26–A28.
24. Zimmerman M. *Diagnosing DSM-IV psychiatric disorders in primary care settings*. East Greenwich: Psych Products Press, 1994.
25. Jones DR. Suicide by aircraft. *Aviat Space Environ Med* 1977;48:454–459.
26. Federal Aviation Agency. *Guide for aviation medical examiners. Appendix A, Mental Standards*. 14 Code of Federal Regulations, Class 1, 67.107.a.l; class 2, 67.207.a.l; class 3, 67.307.a.l. Washington, DC: Federal Aviation Agency, 1996:B1-2, Cl-2, D1-2.
27. Jones DR, Patterson JC. Medical or administrative? Personality disorders and maladaptive personality traits in aerospace medical practice. *Aviat Med Q* 1989;2:83–91.Reprinted in AGARD AG-324. Neuilly-sur-Seine, France: NATO Advisory Group for Aerospace Research and Development, 1991:19.1–19.4.
28. Flynn CF, McGlohn S, Miles RE. Occupational outcome in military aviators after psychiatric hospitalization. *Aviat Space Environ Med* 1996;67:8–13.
29. Patterson JC, Jones DR, Marsh RW, et al. Aeromedical management of US Air Force aviators who attempt suicide. *Aviat Space Environ Med* 2001;72:1081–1085.
30. US Air Force. *Medical standards and examination*. Washington, DC: US Air Force, 1994. Air Force Instruction 48–123.
31. van Gerwen LJ, Diekstra RFW. Fear of flying treatment programs for passengers: an international review. *Aviat Space Environ Med* 2000;71:430–437.
32. Jones DR. Fear of flying: no longer a symptom without a disease. *Aviat Space Environ Med* 2000;71:438–440.
33. Mitchell J. When disaster strikes: the critical incident stress debriefing process. *J Emerg Med Serv* 1983;8:36–39.
34. Lange M, O'Neill HJ. Serotonin reuptake inhibitors and the depressed pilot [Abstract 101]. *Aviat Space Environ Med* 2000;71:290.
35. Paul M, Gray G, Lange M. The effect of sertraline on psychomotor performance [Abstract 146]. *Aviat Space Environ Med* 2001;72:260.
36. Sommese T, Patterson JC. Acute effects of cigarette smoking withdrawal: a review of the literature. *Aviat Space Environ Med* 1995;66:164–167.
37. Air Transport Medicine Committee. *Medical guidelines for airline travel*. Washington, DC: Aerospace Medical Association, 1997.
38. Jones DR. Aeromedical transportation of psychiatric patients: historical review and present management. *Aviat Space Environ Med* 1980;51:709–716.
39. Shneidman E. *Definition of suicide*. New York: Wiley, 1985.
40. Grinker RR, Spiegel JA. *Men under stress*. Philadelphia: Blakiston, 1945.
41. Jones DR. US Air Force combat psychiatry. In: Jones FD, Sparacino LR, Wilcox VL, ed. et al. *War psychiatry*. Washington, DC: Office of the Surgeon General at TMM Publications, Borden Institute, Walter Reed Army Medical Center, 1995:177–210.
42. Vaillant GE. *Adaptation to life*. Boston: Little, Brown and Company, 1977:383–386.

RECOMMENDED READINGS

Jones DR. Military psychiatry. In: Sacks MH, Sledge WH, Warren C, eds. *Core readings in psychiatry: an annotated guide to the literature*, 2nd ed. Washington, DC: American Psychiatric Press, 1995:781–796.

Levy NA. *Personality disturbances in combat fliers*. New York: Josiah Macy, Jr. Foundation, 1945.

Levy RA. Psychiatry. In: Rayman RB, Hastings JD, Kruyer WB, et al., eds. *Clinical aviation medicine*, 3rd ed. New York: Castle Connolly Graduate Medical Publishing, 2000:289–312.

McFarland RA. *Human factors in air transportation*. New York: McGraw-Hill, 1953.

Perry CJG, ed. Psychiatry in aviation medicine. *Int Psychiatry Clin* 1967;4:1–222.

Sledge WH. Aerospace psychiatry. In: Kaplan HI, Freedman AM, Sadock BJ, eds. *Comprehensive textbook of psychiatry*, 3rd ed. Baltimore: Williams & Wilkins, 1980:2902–2914.

Stokes A, Kite K. *Flight stress: stress, fatigue, and performance in aviation*. Brookfield: Ashgate, 1994.

CHAPTER 18

Endocrine System and Nephrology

Paula A. Corrigan and Curtiss B. Cook

Balance, to my mind, is the key word.

—Sir Alexander Campbell

The relative severity of a given condition, and its potential impact on safe aviation performance, are considerations determining the medical certification status of an airman. With respect to flight performance, the effect of any endocrine or renal disorder on cognition, judgment, alertness, consciousness, affect, and stamina pinpoint the primary safety concerns. The medical history of a given aviator is first obtained and summarized with attention to the issues described earlier. The current physical status is then assessed along with any potential treatment. If current medical practice results in "normalization" of an individual with an endocrine or renal disorder, and if the aeromedical risk assessment is determined to be favorable, aeromedical certification may be possible.

Diseases of the endocrine and renal systems span a wide variety of disorders, including diseases of glucose and lipid metabolism; the thyroid, pituitary, adrenal, and reproductive function; nephrolithiasis; acute and chronic renal failure; and neoplasms of both systems. It is beyond the scope of this chapter to provide a comprehensive review of the diverse pathology encountered in the fields of endocrinology and nephrology. This section, therefore, focuses on five of the most commonly encountered types of disorders that the aerospace medicine physician will likely encounter: diabetes mellitus, functional thyroid disease, nephrolithiasis, hematuria, and proteinuria.

DIABETES MELLITUS

Classification and Diagnosis

In 1997, new consensus was reached on the classification of diabetes mellitus. The terms *juvenile-onset diabetes* or *insulin-dependent diabetes* were dropped in favor of the term *type* 1 *diabetes*. The terms *adult-onset diabetes* or *non–insulin-dependent diabetes* were dropped in favor of the term *type* 2 *diabetes*. Other specific types were also recognized (e.g., drug induced). The new nosology was intended to be consistent with contemporary understanding of the pathophysiology for different forms of diabetes (1).

In addition to the revised classification of diabetes, a modification was made in diagnostic criteria (1). The principle change was the diagnostic cutoff for fasting plasma glucose level, which was lowered from 140 to 126 mg/dL. The diagnosis of diabetes in a nonpregnant adult is made when one of the following criteria are satisfied: (i) fasting glucose level of 126 mg/dL or more, (ii) 2-hour glucose level of 200 mg/dL or more following a standard 75 g oral glucose challenge, or (iii) a random glucose level of 200 mg/dL plus symptoms consistent with diabetes (e.g., polyuria, polydipsia). When using criteria (i) or (ii), confirmatory testing on a separate day to rule out a false-positive result is required before making the final diagnosis of diabetes. The hemoglobin A_{1c} is not favored to establish the diagnosis of diabetes, although criteria have been proposed (2).

Epidemiology

Diabetes mellitus is one of the most common endocrine disorders, affecting approximately 6% of the world's population (3). Type 2 diabetes constitutes most diabetes cases. Diabetes is epidemic in the United States with an estimated prevalence of approximately 7% of the population (4). Projections about future increases in prevalence predict a continued and rapid rise in the number of affected individuals both nationally and globally (3,5).

Aeromedical Concerns

Diabetes mellitus is associated with numerous complications, all of which have potential aeromedical implications. Acute complications may develop that include diabetic ketoacidosis, hyperglycemic crisis, and hypoglycemia. Chronic complications are also critical for aeromedical certification. Diabetes is now the leading cause of adult blindness in the United States, and the number one cause of end-stage renal disease and lower extremity amputations (6). Neuropathic complications can involve both the peripheral and autonomic nervous systems, and the involvement of autonomic nervous system can result in orthostatic hypotension, gastroparesis, bladder dysfunction, and impairment of the patient's ability to detect hypoglycemia (hypoglycemic unawareness). Individuals with diabetes are at high risk for vascular disease in all vascular territories. Cardiovascular disease remains the leading cause of mortality in diabetes; because of autonomic neuropathy, patients with diabetes may have silent myocardial ischemia (7).

In addition to the aeromedical considerations that arise from chronic diabetes complications, additional concerns relate to the direct effects of hyper- and hypoglycemia on cognitive function and those that arise due to medical therapy. Studies have demonstrated impaired cognitive function and mood with an acute rise in blood glucose levels (8). There is also data showing that acute hypoglycemia can lead to impaired nonverbal intelligence, and recurrent hypoglycemia has been reported to lead to permanent neuropsychological impairment (9–11), although this latter finding has not always been consistent (12). Repeated episodes of hypoglycemia can lead to autonomic failure and worsen hypoglycemia unawareness (13).

In addition to chronic complications and the impact of extreme glucose values on cognitive impairment, the third aeromedical concern related to diabetes is that of pharmacotherapy. Chronic complications of diabetes are related to the severity and duration of hyperglycemia, hypertension, and hyperlipidemia; simultaneous management of these metabolic abnormalities is needed to prevent or delay the onset of the potentially disabling associated conditions of retinopathy, neuropathy, renal disease, and cardiovascular disease (14–18). Care guidelines, including what targets to achieve for hemoglobin A_{1c}, blood pressure, and lipids are well published (19). Current understanding of the pathophysiology of type 2 diabetes must also take into account the progressive loss of pancreatic β-cell function. Consequently, as the duration of diabetes increases, combined and often complex pharmacotherapies are needed to maintain good glycemic control (20). Eventually, insulin therapy may be needed to achieve glucose targets. These complex therapies for hyperglycemia are typically in addition to the other medications needed to control hypertension and hyperlipidemia. Therefore, polypharmacy may be an issue in the aviator, and the potential side effects and interactions from multiple drugs need to be assessed as part of any aeromedical evaluation.

At the time of publication, in the United States, the Federal Aviation Administration (FAA) is the only aeromedical authority that allows medical certification of noncommercial pilots with type 1 diabetes, and only under strictly limited conditions (see Chapter 11). The FAA, as well as all U.S. military medical authorities, allow some type 2 diabetic patients under good control to fly, with each authority setting specific restrictions (21).

THYROID DISEASE

Epidemiology and Diagnosis

The most common types of thyroid disease (hypothyroidism, hyperthyroidism, goiters, or nodules) may occur with high frequency in the general population. As many as 50% of persons may have microscopic nodules, 15% palpable goiters, and 10% of the general population an abnormal thyroid-stimulating hormone (TSH) level (22). The prevalence of newly diagnosed hypothyroidism in women is approximately 10 times greater than in men. The prevalence of thyrotoxicosis is 0.5% to 2.0% in women, and is also 10-fold greater in women than in men (23). In addition to female gender, the aeromedical examiner should be aware of other risk factors for thyroid disease including older age, history of previous thyroid dysfunction, presence of other autoimmune conditions, use of certain medications (e.g., amiodarone, lithium), and a family history of thyroid disease. The American Thyroid Association recommends biochemical screening for thyroid disease in asymptomatic individuals beginning at age 35 and then every 5 years thereafter (24).

The serum TSH is regarded as the most reliable laboratory method of screening for hypothyroidism and hyperthyroidism in ambulatory patients (24). With the advent of improved TSH assays, instances of subclinical hypothyroidism and hyperthyroidism have been recognized (25). It should be noted that the TSH alone does not identify patients with central hypothyroidism resulting from hypothalamic or pituitary disease. Central hypothyroidism should be suspected in cases where free thyroxine (FT_4) is low in conjunction with a TSH that is inappropriately low or normal. An elevated TSH accompanied by high thyroxine levels should lead the clinician to suspect either generalized resistance to thyroid hormone or a TSH secreting pituitary adenoma.

Hypothyroidism

Primary hypothyroidism is defined as signs and symptoms accompanied by an elevated TSH. A case where the TSH is elevated and the FT4 is normal with minimal or no symptoms is classified as *subclinical* or *mild hypothyroidism*. Thyroid hormone has an impact on nearly every organ system, and the severity of hypothyroid symptoms depends on patient age, how rapidly the hypothyroid state evolved, and the presence of other comorbidities. Symptoms are generally nonspecific, and can be confused with other coexisting disorders (e.g., depression). The underlying problem is the slowing of many physiologic processes, but from an aeromedical standpoint, the effects of untreated hypothyroidism on cardiac, pulmonary, and behavioral function could have the greatest impact on the aviator.

Cardiovascular changes due to hypothyroidism can include bradycardia, increased systemic vascular resistance, and decreased cardiac contractility. Low-voltage and nonspecific ST changes may be seen on electrocardiogram. Up to 40% of persons may have diastolic hypertension. Pulmonary function and respiratory function are also altered in hypothyroidism including conditions such as sleep apnea. Hypercapnia due to decreased ventilatory response to carbon dioxide can occur. The behavioral and neuropsychological symptoms from hypothyroidism are nonspecific. Cognitive impairment, memory deficits, and psychomotor slowing may all be present. Patients may complain of depression, sleep disturbances, and fatigue (23).

The signs and symptoms of hypothyroidism are typically reversed with adequate replacement of thyroid hormone. Signs and symptoms that do not resolve after achieving a normal TSH are likely due to some other cause and need to be evaluated. Thyroid hormone replacement is best made with one of the synthetic thyroxine preparations. These are well tolerated and do not have adverse effects that would impair the aviator's performance.

Hyperthyroidism

Thyrotoxicosis is defined as signs and symptoms that accompany elevations in free thyroxine and triiodothyronine, and the TSH is below the lower limit of normal. The term *hyperthyroidism* refers to sustained increases in thyroid hormone biosynthesis and secretion by the thyroid gland (24). Suppressed TSH levels in the face of normal FT4 and relative absence of symptoms is often referred to as *subclinical* or *mild hyperthyroidism*. It is now recognized that even this condition can negatively impact health; subclinical hyperthyroidism is particularly relevant to aeromedical disposition as there is a higher risk of atrial fibrillation (25). The two most common causes of hyperthyroidism the aeromedical examiner is likely to encounter are autoimmune and from a toxic nodule.

Nearly every organ system can be negatively impacted by prolonged exposure to elevated thyroxine levels. From an aeromedical standpoint, some of the greatest concerns relate to effects on the cardiopulmonary system, neurobehavioral symptoms, and treatment side effects. Cardiopulmonary manifestations of thyrotoxicosis include decreased systemic vascular resistance, increased cardiac output, tachycardia, and sometimes supraventricular dysrhythmias (e.g., atrial fibrillation). Patients will often experience palpitations. Patients frequently describe tachypnea, dyspnea on exertion, and decreased exercise tolerance. There are physiologic increases in oxygen consumption and minute ventilation, and pulmonary mechanics can be affected with decreased lung compliance and respiratory muscle weakness. Neurobehavioral symptoms can be profound and could have potentially severe implications for flying. Anxiety, dysphoria, insomnia, tremulousness, and cognitive dysfunction can be present. Frank psychosis may occur in newly diagnosed thyrotoxicosis, and emotional lability can be severe (23).

The therapeutic goal when treating thyrotoxicosis is to return the patient to biochemical and clinical euthyroidism. Adjunctive therapy (e.g., β-blockers) to ameliorate symptoms may be needed until thyroid levels begin to normalize. Treatment of thyrotoxicosis depends on the etiology, but for the most common causes of thyrotoxicosis listed above, one of three methods are usually employed—use of thionamide medications (e.g., propythiouracil or methimazole), ablation with radioactive iodine, or surgical thyroidectomy. Thionamides do have rare adverse events such as marrow suppression or hepatotoxicity, but side effects that are more common include arthralgia, altered taste, or fever; some of these effects could be of aeromedical concern.

NEPHROLITHIASIS

Epidemiology and Pathophysiology

Nephrolithiasis (renal system stones) is a common urinary tract disorder, affecting approximately 5% of the population, with a lifetime risk of up to 12% of passing a stone. Men are affected more frequently than women, with a ratio of approximately 1.5:1. The peak age for men is 30 years; women have bimodal peaks at age 35 and 55 years (26). Renal stones are frequently an incidental finding in aviators presenting for an examination. Approximately one third of asymptomatic renal stones are expected to become symptomatic within 3 years, with the likelihood related to the location and size of the stone. Once nephrolithiasis is diagnosed, the risk of a recurrent stone is up to 50% within 5 years (27). A family history of stones increases risk by three times; certain medical conditions (insulin resistance, hypertension, primary hyperparathyroidism, gout, surgical menopause) or anatomic abnormalities of the urinary tract are also associated with increased risk. Certain drugs (such as decongestants, diuretics, probenecid, carbonic anhydrase inhibitors, and protease inhibitors) can also predispose to nephrolithiasis. A specific causal factor for renal stones is not found in most cases (26). Low urine volume is the most common associated abnormality, and is the most important factor to address in order to avoid recurrences. Several studies have reported an increased incidence of renal stones compared to the general population in some military aviators, mainly due to dehydration precipitated by austere living conditions or prolonged flights (28,29). Another study demonstrated that increasing daily urinary volume in astronauts just returned from spaceflight reduced the risk of forming renal stones (30).

Approximately 70% to 80% of patients with nephrolithiasis have calcium-based stones, most of which are calcium oxalate, or less frequently, calcium phosphate. Hypercalciuria (defined as >200 mg/24 hr or >4 mg/kg/24 hr excreted) is identified in 60% to 80% of calcium stone formers (26). The other main types of stones include uric acid (5%–10%), struvite (15%), and cystine (1%). The same patient may be identified with more than one type of stone. Uric acid stones develop when the urine is saturated with uric acid such as occurs with dehydration, or with an acidic pH of the urine. Struvite stones form in patients with urinary tract infections due to urease producing organisms such as *Proteus* or *Klebsiella*. Struvite (magnesium ammonium phosphate) is also the most common component of staghorn calculi, which can cause obstruction. Cystine stones are the result of a rare inherited renal defect causing overexcretion of cystine. Stones in these patients usually begin in childhood and can eventually lead to end-stage renal disease.

Patient Evaluation and Treatment

The clinical course of a symptomatic aviator with a renal stone is usually that of gradual onset of flank, abdominal, or back pain that progresses to acute colicky pain. Renal colic is usually described as sharp, severe, and localized to the flank, and may be associated with nausea and vomiting. The pain may occur episodically and may radiate anteriorly over the abdomen, or may be referred to the *ipsilateral groin area*. Once a stone enters the ureter, particularly at the ureterovesicular junction, lower urinary tract symptoms may occur such as dysuria, urgency, and frequency. Urinalysis should be obtained for all patients. Although microscopic hematuria combined with typical symptoms is highly predictive of nephrolithiasis, stones may occur with the absence of blood in the urine (31). Crystals may be present on urine microscopic examination, such as the hexagonal crystals seen in cystinuria, or the "coffin lid" shaped struvite crystals. Urine pH is a valuable clue to the cause of the possible stone; persistent pH below 5.5 is suggestive of uric acid or cystine stones, both usually radiolucent on x-ray films. Persistent urine pH above 7.2 is suggestive of struvite stones.

For initial evaluation, a plain kidney-ureter-bladder (KUB) radiograph can be obtained to determine if the stones are radiopaque or radiolucent. Noncontrast helical computed tomography (CT) is the best imaging method to confirm the diagnosis of a urinary stone (99% diagnostic accuracy) in a patient with acute flank pain; it also helps with the measurement of stone density and can detect urinary tract obstruction. Additionally, if the symptoms are not caused by a renal stone, CT can often reveal the true source of the pain. Intravenous pyelogram (IVP) was the gold standard for diagnosis before CT, and is still utilized if CT is not possible. Ultrasonography is rarely used because of its low sensitivity, but is sometimes performed as the initial study in pregnant patients, and is very sensitive for the diagnosis of renal outflow obstruction.

An aviator who develops a symptomatic ureteral stone should be grounded until the stone passes or it is removed, because it is possible for incapacitating pain to occur at any time. Most ureteral calculi less than 5 mm in diameter will pass spontaneously within 4 weeks. A recent study found that the α-adrenergic blocker tamsulosin combined with corticosteroids hastened the passage of stones and reduced the need for analgesics (32). Once the acute stone episode is over, a full metabolic evaluation for possible underlying causes of stone disease should be performed, and any available stones should be analyzed. If a metabolic abnormality is discovered, consideration of prophylactic agents such as thiazides, potassium citrate, or allopurinol may be considered. An increased fluid intake of at least 2.5 to 3.0 L/d is advisable. Dietary modifications may be recommended based on the type of stone, including reduced oxalate intake (such as found in rhubarb, spinach, beets, okra, sweet potatoes, sesame seeds, nuts, chocolate, and soy products), reduced animal protein, and reduced sodium intake. Dietary restriction of calcium is not recommended because calcium consumed at meals (such as in dairy products) may help to reduce oxalate absorption and thereby reduce risk of stone formation (33).

Surgical intervention may become necessary if the stone does not pass, refractory symptoms occur, or acute obstruction develops. Extracorporeal shock wave lithotripsy (ESWL) is commonly used to fragment stones in the renal system. ESWL usually has minor complications, and most individuals recover within a few weeks, although recent studies have implicated an increased risk of development of hypertension and diabetes in the long term (34). With the event of the flexible scope, ureteroscopy may now be used to extract stones from the entire urinary tract, and may be used for proximal stones if ESWL fails or is contraindicated. Percutaneous nephrolithotomy (PN) creates an access tract into the renal collecting system through which nephroscopy can be performed, and is typically used for proximal stones, especially for multiple, large (>2 cm), or staghorn calculi. Recovery from PN may take several weeks. There is currently a limited role for open surgery, which has a much longer recovery time and more potential complications.

Aeromedical Concerns

Sudden incapacitation in-flight due to the pain of renal colic is the main aeromedical concern associated with renal stones. One study reviewing causes of in-flight incapacitation in United States Air Force (USAF) aircrew revealed three cases of in-flight events over a 10-year period caused by renal colic. All three episodes involved pilots, and in each case, including one single-seat aircraft, the plane landed without incident (35). Another study found renal colic as the cause of nonfatal in-flight incapacitation in 4 out of 42 pilots of International Air Transport Association (IATA) member airlines between 1960 and 1966 (36). Yet another study by the Civil Aerospace Medical Institute (CAMI) revealed that 3 of 39 incapacitating events of U.S. airline pilots during the period 1993 to 1998 were due to renal colic; none were associated with aircraft accidents (37).

The issue of asymptomatic retained renal stones or nephrocalcinosis is a difficult one for the aeromedical examiner. As mentioned earlier, there is a 30% chance that an asymptomatic retained stone will become symptomatic within 3 years. Stones retained in the renal parenchyma, or within cysts or calyceal diverticula, are unlikely to migrate into the collecting system and can therefore usually be followed with serial radiographs or ultrasonography. Stones retained in a papillary duct or more distal kidney parenchyma are more likely to migrate into the collecting system, and may be considered for surgical intervention. Additionally, it is possible that the aviation environment can contribute to the growth and movement of retained renal stones due to voluntary dehydration, extreme temperature, and sedentary work commonly experienced by aircrew. Therefore, it is imperative for aircrew with known nephrolithiasis to remain well hydrated, particularly in the flying environment.

Aviators with a single episode of nephrolithiasis are likely to be returned to flying after they are proved to be stone-free with negative metabolic evaluation, by both civil and military aviation authorities. Recurrent or retained stones will require a waiver or special issuance that will depend on the location and type of stone, need for therapy, and complications such as impaired renal function.

HEMATURIA

It is common practice to obtain a urine dipstick as part of a flight physical examination for aviators. Therefore, the aeromedical examiner will frequently be required to evaluate microscopic hematuria and proteinuria, both of which can be benign conditions, but can also herald underlying urinary tract or kidney disease. This section addresses the evaluation of hematuria, whereas the next section discusses proteinuria.

Etiology and Diagnosis

Hematuria is a fairly common condition. In younger patients, hematuria is transient and benign, and may be secondary to strenuous exercise (such as in a high G-force environment). However, in older patients (>40 years), there is an appreciable risk of malignancy, even if the hematuria is transient, especially in patients with a history of smoking. Hematuria may be visible or microscopic. Gross hematuria is suspected when the urine appears red or brown. As little as 1 mL of blood per liter can induce a visible color change; red or brown urine can also be seen in conditions other than bleeding such as hemolytic anemia, porphyria or the ingestion of beets, blackberries, or certain medications. Gross hematuria is characteristic of lower urinary tract disease and/or bleeding diatheses, and rarely indicates kidney disease, with the exception of cyst rupture in polycystic kidney disease and immunoglobin (IgA) nephropathy. Microscopic hematuria is not visible, but red blood cells (RBCs) are seen on microscopic examination. Definitions vary, but the American Urologic Association requires greater than or equal to 3 RBCs per high-power field to diagnose microscopic hematuria. Dipstick testing for heme may be too sensitive; therefore, a positive dipstick should always be confirmed with microscopic examination. The prevalence of microscopic hematuria is high, occurring in 1.2% to 5.2% in young adult males, and up to 16% of the general population (38). A study of male soldiers with an annual urinalysis performed over a 12-year period showed a cumulative incidence of transient microscopic hematuria of 39% (39).

If microscopic hematuria is persistent on repeat examination, and there is no evidence of a benign cause such as menstruation, vigorous exercise, sexual activity, viral illness, trauma, or infection, then further evaluation is warranted. Hematuria of glomerular origin is frequently associated with an active urinary sediment such as red blood cell casts, dysmorphic red cells, proteinuria, and possibly an elevated serum creatinine. The most common intrarenal sources of hematuria include IgA nephropathy, hereditary nephritis (Alport syndrome), thin-basement membrane nephropathy, or focal glomerulonephritis of other causes. If an intrarenal cause is suspected, referral should be made to a nephrologist for evaluation of primary renal disease with possible kidney biopsy. In the absence of glomerular findings, or if the patient is older than 40 years, a smoker, or has a history of urologic problems per gross hematuria, a urologic referral should be made. Common causes of extrarenal hematuria include stones, infection, and malignancy.

Aeromedical Concerns

While transient hematuria is typically benign, persistent or recurrent hematuria may be a sign of significant underlying urinary tract disease and must be fully evaluated in all aviators. Occasionally, a thorough evaluation of the urinary system fails to identify the source of hematuria, thereby posing a dilemma for the aeromedical examiner. Follow-up studies of patients with unexplained microscopic hematuria suggest that these patients have a benign course, and could be allowed to remain on flying status. One study of 191 patients with asymptomatic hematuria that remained unexplained after full urologic evaluation including cytology and cystoscopy showed no cancers detected during long-term follow-up (40). Another study followed 161 Israeli Air Force members with asymptomatic microscopic hematuria over a mean follow-up of 7.6 years. Ninety-one out of 161 of these individuals had no further renal evaluation, but did not develop urologic malignancies or serious progressive renal disorders over the period of follow-up (39).

PROTEINURIA

Etiology and Diagnosis

Although a wide variety of conditions, ranging from benign to lethal, can cause proteinuria, fewer than 2% of patients whose urine dipstick test is positive for protein have serious underlying urinary tract disorders (41). Urinary protein excretion in the normal adult should be less than 150 mg/d, which correlates with a negative dipstick test. Excretion rates above this define proteinuria and should be evaluated. Alkaline or concentrated urine; gross hematuria; and the presence of mucus, semen, or white blood cells can cause a dipstick urinalysis to be falsely positive for protein. Dilute urine (>1.015) can result in a false negative dipstick. Several factors may lead to mildly increased protein excretion rates of up to 300 mg/d (trace to 1+ protein on dipstick) in normal patients. These factors include strenuous exercise (such as during exposure to high G forces), fever, viral illness, or dehydration. If a repeat urine dipstick done at least 48 hours after rest or recovery from illness demonstrates no protein, transient proteinuria is diagnosed, and no further evaluation is indicated. Increased protein excretion (≤1 g/d) upon standing is known as *orthostatic proteinuria*, a benign condition that occurs in approximately 3% to 5% of adolescents and young adults. If this condition is suspected, overnight urine collection will show less than 50 mg protein excreted for an 8-hour collection (41).

For persistent or significant (≥2+) proteinuria, the initial step in diagnosis is careful examination of the urinary sediment for red or white blood cells, casts, or crystals. These findings give useful clues to infection, glomerulonephritis, urolithiasis, or interstitial nephritis, as sources of proteinuria. Concomitantly, a 24-hour urine for protein and creatinine clearance should be initiated to quantify precisely the protein excretion rate. An alternative to the 24-hour urine specimen is the urine protein-to-creatinine ratio (UPr/Cr), determined in a random urine specimen. A UPr/Cr ratio of less than 0.2 mg is equivalent to 200 mg/d of protein excreted and is considered normal (41). Calculation of the glomerular filtration rate (GFR) is also helpful, and can indicate significant renal dysfunction much earlier than changes in serum creatinine will occur. Additionally, one study found that proteinuria in combination with reduced GFR was a significant predictor of cardiovascular disease and all-cause mortality (42). The most common reasons for proteinuria in the range of up to 2 g/d with normal urine sediment and reduced creatinine clearance are diabetes, hypertension, and systemic lupus erythematosus. Therefore, screening should include blood pressure screening, fasting blood sugar, and antinuclear antibodies. Proteinuria greater than 2 g/d suggests glomerular disease, and referral to a nephrologist for further evaluation is indicated.

Aeromedical Concerns

Proteinuria is not a disease itself, but suggestive of a possible underlying disorder which could have aeromedical implications. If entities such as hypertension, renal calculi, or diabetes mellitus are found, flying status will be dictated by the underlying problem. It should be stressed that diagnostic steps should be followed logically and expeditiously until a satisfactory explanation of persistent proteinuria is accomplished. Treatment with medications such as angiotensin-converting enzyme inhibitors or angiotensin receptor blockers is recommended for some etiologies of proteinuria, and these are normally well tolerated and compatible with flying duties, if the underlying disease is controlled. Additionally, conditions associated with the aviation environment such as hypoxia or high G forces may cause transient proteinuria with a physiologic basis. There is no evidence to suggest that repeated transient proteinuria related to these factors will cause chronic renal effects in aviators without underlying systemic disease (43).

REFERENCES

1. The Expert Committee on the Diagnosis and Classification of Diabetes Mellitus. Report of the Expert Committee on the Diagnosis and Classification of Diabetes Mellitus. *Diabetes Care* 1997;20(7):1183–1197.
2. Barr RG, Nathan DM, Meigs JB, et al. Tests of glycemia for the diagnosis of type 2 diabetes mellitus. *Ann Intern Med* 2003;137: 263–272.
3. Adeghate E, Schattner P, Dunn E. An update on the etiology and epidemiology of diabetes mellitus. *Ann N Y Acad Sci* 2006; 1084:1–29.
4. Cowie CC, Rust KF, Byrd-Holt DD, et al. Prevalence of diabetes and impaired fasting glucose levels in adults in the U.S. population: national health and nutrition examination survey 1999–2002. *Diabetes Care* 2006;29(6):1263–1268.
5. Boyle JP, Honeycutt AA, Venkat Narayan KM, et al. Projection of diabetes burden through 2050. *Diabetes Care* 2001;241:1936–1940.
6. Centers for Disease Control and Prevention Division of Disease Translation. 1999 Diabetes Surveillance report. *CDC's diabetes public health resource Website.* DHHS; 2000.
7. Maser RE, Lenhard MJ. Cardiovascular autonomic neuropathy due to diabetes mellitus: clinical manifestations, consequences, and treatment. *J Clin Endocrinol Metab* 2005;90(10):5896–5903.
8. Cox D, Kovatchev B, Gonder-Frederick L, et al. Relationships between hyperglycemia and cognitive performance among adults with type 1 & type 2 diabetes. *Diabetes Care* 2005;28:71–77.
9. Warren R, Allen K, Sommerfield A, et al. Acute hypoglycemia impairs nonverbal intelligence: importance of avoiding ceiling effects in cognitive function testing. *Diabetes Care* 2004;27:1447–1448.
10. Wredlin R, Levander S, Adamson U, et al. Permanent neuropsychological impairment after recurrent episodes of severe hypoglycaemia in man. *Diabetologia* 1990;33:152–157.
11. Langan S, Deary I, Hepburn D, et al. Cumulative cognitive impairment following recurrent severe hypoglycaemia in adult patients with insulin-treated diabetes mellitus. *Diabetologia* 1991;34(5):337–344.
12. Kramer L, Fasching P, Madl C, et al. Previous episodes of hypoglycemic coma are not associated with permanent cognitive brain dysfunction in IDDM patients on intensive insulin treatment. *Diabetes* 1998;47(12):1909–1914.
13. Cryer PE. Hypoglycemia: the limiting factor in the glycaemic management of type I and type II diabetes. *Diabetologia* 2002;45: 937–938.
14. Stratton IM, Adler AI, Neil HAW, et al. Association of glycaemia with macrovascular and microvascular complications of type 2 diabetes (UKPDS 36): prospective observational study. *Br Med J* 2000;321:405–412.
15. Adler AI, Stratton IM, Neil HAW, et al. Association of systolic blood pressure with macrovascular and microvascular complications of type 2 diabetes (UKPDS 36): prospective observational study. *Br Med J* 2000;321:412–419.
16. Gaede P, Vedel P, Larsen N, et al. Intensified multifactorial intervention in patients with type 2 diabetes mellitus and microalbuminuria: the Steno type 2 randomized study. *Lancet* 1999;353: 617–622.
17. Gaede P, Vedel P, Larsen N, et al. Multifactorial intervention and cardiovascular disease in patients with type 2 diabetes. *N Engl J Med* 2003;348:383–393.
18. Heart Protection Study Collaborative Group. MRC/BHF heart protection study of cholesterol lowering with simvastatin in 20,536 high-risk individuals: a randomized placebo-controlled trial. *Lancet* 2002;360:7–22.
19. American Diabetes Association. Standards of medical care in diabetes—2007. *Diabetes Care* 2007;30:S4–S41.

20. Turner RC, Cull CA, Frighi V, et al. Glycemic control with diet, sulfonylurea, metformin, or insulin in patients with type 2 diabetes mellitus: progressive requirement for multiple therapies (UKPDS 49). *JAMA* 1999;281:2005–2012.
21. Steinkraus LW, Cayce W, Golding A. Diabetes mellitus type 2 in aviators: a preventable disease. *Aviat Space Environ Med* 2003;74: 1091–1100.
22. Wang C, Crapo L. The epidemiology of thyroid disease and implications for screening. *Endocrinol Metab Clin North Am* 1997; 26(1):189–218.
23. Braverman LE, Utiger RD, eds. *Werner and Ingbar's the thyroid: a fundamental and clinical text*. Philadelphia: Lippincott Williams & Wilkins, 2005.
24. Ladenson PW, Singer PA, Ain KB, et al. American thyroid association guidelines for detection of thyroid dysfunction. *Arch Intern Med* 2000;160(11):1573–1575.
25. Surks MI, Ortiz E, Daniels GH, et al. Subclinical thyroid disease: scientific review and guidelines for diagnosis and management. *JAMA* 2004;291(2):228–238.
26. Parmar MS. Kidney stones. *Br Med J* 2004;328:1420–1424.
27. Pearle MS, Calhoun EA, Curhan GC. Urologic DISEASES in America Project: urolithiasis. *J Urol* 2005;173(3):848–857.
28. Clark JY. Renal calculi in army aviators. *Aviat Space Environ Med* 1990;61:744–747.
29. Cramer JS, Forrest K. Renal lithiasis: addressing the risks of austere desert deployments. *Aviat Space Environ Med* 2006;77:649–653.
30. Whitson PA, Pietrzyk RA, Sams CF. Urine volume and its effects on renal stone risk in astronauts. *Aviat Space Environ Med* 2001; 72:368–372.
31. Miller NL, Lingeman JE. Management of kidney stones. *Br Med J* 2007;334:468–472.
32. Dellabella M, Milanese G, Muzzonigro G. Randomized trial of the efficacy of tamsulosin, nifedipine and phloroglucinol in medical expulsive therapy for distal ureteral calculi. *J Urol* 2005; 174:167–172.
33. Curhan GC, Willett WC, Speizer FE, et al. Comparison of dietary calcium with supplemental calcium and other nutrients as factors affecting the risk for kidney stones in women. *Ann Droit Int Med* 1997;126(7):497–504.
34. Krambeck AE, Gettman MT, Rohlinger AL, et al. Diabetes mellitus and hypertension associated with shock wave lithotripsy of renal proximal ureteral stones at 19 years of follow up. *J Urol* 2006;175:1742–1747.
35. McCormick TJ, Lyons TJ. Medical causes of in-flight incapacitation: USAF experience 1978–1987. *Aviat Space Environ Med* 1991;62: 884–887.
36. Buley LE. Incidence, causes and results of airline pilot incapacitation while on duty. *Aerosp Med* 1969;40(1):64–70.
37. DeJohn CA, Wolbrink AM, Larcher JG. *In-Flight Medical Incapacitation and Impairment of U.S. Airline Pilots:1993 to 1998. DOT/FAA/AM-04/16*. Washington, DC: Office of Aerospace Medicine, Oct 2004.
38. Grossfeld GD, Wolf JS, Litwin MS, et al. Evaluation of asymptomatic microscopic hematuria in adults: summary of the AUA best policy recommendations. *Am Fam Physician* 2001;63(6): 1145–1154.
39. Froom P, Ribak J, Benbassat J. Significance of microhaematuria in young adults. *Br Med J* 1984;288:20–22.
40. Howard RS, Golin AL. Long-term follow-up of asymptomatic microhematuria. *J Urol* 1991;145:335–336.
41. Carroll MF, Temte JL. Proteinuria in adults: a diagnostic approach. *Am Fam Physician* 2000;62:1333–1340.
42. Irie F, Iso H, Sairenchi T, et al. The relationships of proteinuria, serum creatinine, glomerular filtration rate with cardiovascular disease mortality in Japanese general population. *Kidney Int* 2006; 69:1264–1271.
43. DeLonga DM. Proteinuria in aviation personnel: waiver policy in the U.S. Navy. *Aviat Space Environ Med* 2003;74:664–668.

RECOMMENDED READINGS

American Diabetes Association. Standards of medical care in diabetes—2007. *Diabetes Care* 2007;30:S4–S41.

Braverman LE, Utiger RD, eds. *Werner and Ingbar's the thyroid: a fundamental and clinical text*. Philadelphia: Lippincott Williams & Wilkins, 2005.

David JR, David PG. In: Ernsting J ed. *Aviation Medicine*, 4th ed. London: Hodder Arnold, 2006:637–654.

Rayman RB, John DH, William BK, et al., eds. *Clinical aviation medicine*, 4th ed. New York: Castle Connolly Graduate Medical Publishing, 2006:43–47, 277–289.

CHAPTER 19

Infectious Diseases

Glenn W. Mitchell and Gregory J. Martin

Diseased Nature oftentimes breaks forth in strange eruptions.

—*King Henry IV. Part I. Act iii. Sc. 1.* William Shakespeare (1564–1616)

HISTORICAL PERSPECTIVE

Travel has been a significant vector for infectious diseases since the beginning of time. The spread of the Black Death in the 14th and 15th centuries is a vivid example of the problems of travel when a highly contagious disease is introduced into a nonimmune population (1). People traveled to avoid the plague as it entered their towns, but they were already incubating the disease and only spreading it further. Slow transportation by foot, horse, and carriage kept the plague from exhausting its pool of new victims for many years. The introduction of smallpox, chicken pox, and measles into the New World by Pizzaro and other explorers decimated the indigenous peoples of the Americas and facilitated the cultural dominance of Europeans there. In return, it appears that new world explorers returned to Europe with syphilis, which subsequently became a scourge throughout Europe in the 16th and 17th centuries. Until the late 19th century, lack of understanding of disease transmission led to care for the sick with essentially no effective protective measures for either health care workers or families.

However, acceptance of the "germ theory" and recognition of the need for infection control did not eliminate disease spread because transportation advances continued to increase the ability for infections to be transmitted rapidly across great distances. The influenza pandemic of 1918 provides a good illustration of the role of improving travel modes, as coal- and oil-fired ships provided a faster and more convenient way for persons who were ill to continually expose others to novel diseases; the deploying American troops probably brought influenza with them to Europe from their training camps. Cholera is another disease whose history of increasingly rapid worldwide spread is based on improvements in the speed of travel, thereby permitting infectious passengers and crew to arrive in distant ports and establish novel foci of infection. Outbreaks of cholera in South and Central America during the 1980s illuminated the fact that aircraft are also effective vectors for this disease (2).

Air travel has become a well-recognized and highly visible risk for transmission of infectious agents. The outbreak of Ebola virus in Kitwit, Uganda, in 1978 demonstrated that persons who are ill might well be flown in commercial aircraft without knowledge of risks by the rest of the passengers. Fortunately, more recent studies have demonstrated that direct contact with body fluids is usually necessary for any significant risk for transmission of this disease. The outbreak and threat of worldwide spread of severe acute respiratory syndrome (SARS) in 2002 to 2003 resulted in quarantines and restrictions on air travel, and focused worldwide attention on the impact of air travel on the rapid spread of potentially serious disease across continents. Most recently, commercial aircraft passengers with active tuberculosis (TB), including one case with an extensively drug resistant (XDR) TB strain, have led to intensive discussions in the press and more in-depth investigations of potential problems with spread of infectious diseases inside sealed passenger aircraft cabins (see subsequent text).

Recognition of outbreaks of highly pathogenic avian influenza (HPAI) in birds in many areas of the world and associated human cases has appropriately raised concern for rapid transmission of pandemic influenza through air travel. Unlike TB, which generally requires prolonged, close contact, influenza can be relatively quickly and efficiently transmitted. If HPAI becomes adapted to human-to-human transmission, rapid identification and quarantine of infected patients and their contacts will be needed. In 2005, President of the United States, Bush announced at the United Nations the formation of the International Partnership on Avian and

Pandemic Influenza (IPAPI), which includes management of potentially infected air travelers. The U.S. Department of Health and Human Services has developed a national *Pandemic Influenza Plan* with specific guidelines for travel-associated influenza in a supplement (3).

This chapter will concentrate on diseases of interest to the medical practitioner considering the possible diagnoses for a patient's illness when the condition is associated with a recent history of air travel.

SIGNIFICANT INFECTIOUS DISEASES

Potentially, nearly any infectious agent could be transmitted during air travel. An exhaustive list of potential infectious diseases that could be associated with air travel is too lengthy to compile here. However, a broad sample of significant diseases with their associated common signs and symptoms as well as their relevant characteristics is relevant to the practice of aerospace medicine. For example, travelers may present at varying times after their journey and knowledge of the various incubation periods and geographic locations for common diseases is invaluable. In the interest of brevity, the parasitic diseases and the purely sexually transmitted diseases are not described in this table. These categories of infectious disease do not overlap significantly with those likely to be intentionally spread nor are they commonly spread aboard aircraft. Diseases transmitted in aircraft can be divided as follows:

1. Directly transmitted among passengers. These are mainly respiratory illnesses, and, to a lesser extent, some diarrheal pathogens that can be transmitted in lavatories or through hand-to-hand contact. Viral respiratory pathogens are probably the most commonly transmitted diseases in aircraft. Acute respiratory infections, although exceptionally common, are typically mild. The experience with SARS, and potentially pandemic influenza, demonstrates that very serious respiratory infections may be transmitted in aircraft. These are listed in Table 19-1.
2. Food and waterborne illnesses that are acquired from items served to passengers while on board. These risks are little different from those seen in restaurants and can also be associated with passenger-to-passenger transmission through fomites and are included in Table 19-1.
3. Vector-borne illnesses that are potentially acquired by passengers who are exposed to mosquitoes, sand flies, fleas, or animals that may be intentionally or accidentally on board the aircraft. With the exception of malaria and dengue, transmission of these illnesses aboard aircraft is exceedingly rare; however, the vectors may be transmitted to a nonendemic site and establish the infection in local insects or animals. These potential threats are listed in Table 19-2.
4. Intentionally released agents of bioterrorism such as anthrax, plague, smallpox, and others that could be surreptitiously released in aircraft and with incubation periods would not be detected until the passengers are dispersed throughout the receiving country. Most of the more likely threat agents are listed in Table 19-3.

Table 19-4 gives their common presenting signs and symptoms. More detailed descriptions of each disease can be found in standard medical references (4,5). Control measures, including isolation and personal protection, as well as currently recommended antibiotics should be used appropriately for each disease.

Approximately 50% of travelers to developing countries develop some illness during or after travel and approximately 8% seek medical attention (6). In a country the size of Australia, where 2,000,000 citizens travel overseas each year, this results in approximately 15,000 medical visits. Of course, gastrointestinal infections are most frequent, but various respiratory, cutaneous, and sexually transmitted diseases are also common. The most common life-threatening diagnoses are malaria, dengue, typhoid, amebiasis, and hepatitis. The diagnoses taking the longest time, on average, to manifest are TB, leprosy, and parasitic diseases such as Chagas disease, filariasis, and paragonimiasis. In fact, some do not manifest for months to years after travel. However, more than 90% of these infections (unless the traveler was resident for long periods in developing countries) will become manifest within 6 months of the exposure. Be aware that health problems in immigrants from the developing world often present in the opposite manner, with most infections appearing after 6 months in the new location.

PREVENTIVE ASPECTS OF TRAVEL MEDICINE

The best methods of prevention require education of the traveler and include common sense measures such as careful food selection ("cook it, peel it, boil it, or forget it"), hand washing, avoidance of contact with bodily fluids and lesions, mosquito netting and repellent use, and avoidance of heavily infested areas. Immunization remains the cornerstone of primary prevention of infectious disease. Travelers completing recommended pretravel immunization, such as hepatitis (A and B), yellow fever, rabies, tetanus, polio, measles, mumps, rubella, and varicella, are afforded highly effective protection against these common illnesses. However, other vaccines only reduce—but do not eliminate—the risk of illness, for example, typhoid, meningococcal, and cholera vaccines. Prophylactic medications are the mainstay against several diseases without available vaccines. Diseases with probably effective oral prophylaxis regimens other than vaccines include influenza, plague, leptospirosis, meningococcal meningitis (postexposure), and some types of traveler's diarrhea. Malaria prophylaxis is complicated by regional variation in the presence of multidrug-resistant strains, and the latest recommendation for a region should be researched on websites of the Centers for Disease Control and Prevention (CDC), and the World Health Organization (WHO), or obtained by consultation with a travel medicine specialist before traveling to malarious areas of the world.

Travelers often take medications including antibiotics, purchased either prior to or while traveling, that profoundly

TABLE 19-1

Infectious Agents Potentially Transmitted Among Passengers in Aircraft

Disease	*Major Vector(s)*	*Person-to-person Spread*	*Infectivity*	*Incubation Period*	*Illness Duration*	*Untreated Lethality*	*Vaccine/Antisera Available?*	*Effective Antibiotics?*	*Common Geographic Location(s)*
Respiratory Transmission									
Influenza	Aerosol droplets; fluids	High	High	1–3 d	2–7 d	Low (except for very young and old)	Yes, but organism mutates easily	Antivirals	Worldwide, sometimes in pandemics
Melioidosis (*Pseudomonas pseudomallei*)	Aerosol	Rarely	High: 10–100 organisms	2 d–yr	4–20 d	Variable	No	Yes	Southeast Asia, Central and South America, and Caribbean
Plague (pneumonic *Yersinia pestis*)	Fleas (rats); aerosol	Moderately high	High: 100–500 organisms	2–3 d	1–7 d (usually 2–4 pneumonic)	Very high (~100%)	Yes, but questionably effective for aerosol	Yes	Worldwide
Psittacosis (*Chlamydia psittaci*)	Aerosol (birds)	Very rarely	Moderate	4–15 d	Weeks to months	Very low	No	Yes	Worldwide
Q fever *(Coxiella burnetti)*	Food; aerosol (infected biologicals)	Very rarely	High: 1–10 organisms	10–40 d	2–14 d	Low	Yes	Yes	Worldwide
Smallpox	Contact with infected materials; aerosol	High	High: 10–100 organisms	7–17 d (usually 12)	4 wk (usually 1–2)	High	Yes	Experimental antivirals	Nowhere
Tuberculosis (*Mycobacterium tuberculosis*)	Aerosol (dust and droplets); milk	Yes	Moderate	4–12 wk for IPPD[a] conversion	Years	Moderate if active disease	Yes (BCG[b] is partially effective)	Yes, but lengthy course of multiple drugs	Worldwide

Blood or Body Fluid Transmission									
Congo-Crimean hemorrhagic fever	Ticks; body fluids; aerosol	Moderate	High	3–12 d	Days to weeks	High (~50%)	Experimental; antisera in Bulgaria	Yes	Europe, Africa, Central Asia, Middle East
Ebola virus	Body fluids; aerosol	Moderate	High	7–9 d	2–21 d	Very high (50%–90%)	No	No	Africa
Lassa virus	Body fluids; aerosol	Moderate	High	10–14 d	1–4 wk	Low to moderate (1% overall)	No; antisera experimental	Antivirals	Africa
Rift Valley fever	Mosquitoes; infected biologicals; aerosol	Low	High	2–5 d	Days to weeks	Low	Yes	No	Africa
Food and Fomite Transmission									
Botulism (*Clostridium botulinum)*	Food, water; aerosol	No	$LD_{50} = 0.001\ \mu m/kg$ for Type A	1–5 d	24–72 hr or longer	High	Yes	No	Worldwide
Clostridium perfringens	Food, water; aerosol	No	High	8–12 hr	24 hr	Low	No	No	Worldwide
Hepatitis A	Food; fecal	Yes	High	15–50 d (usually 4 wk)	1–2 wk	Very low	Yes	No	Worldwide
Salmonellosis (*Salmonella* sp)	Food; fecal	Yes	High	6–72 hr (usually 12–36)	1–3 d	Very low (except in very young and old)	No	Yes	Worldwide
Shigellosis (*Shigella* sp)	Food; fecal	Yes	High	12–96 hr	4–7 d	Low (except very young and old)	No	Yes	Worldwide
Staphylococcal enterotoxin B	Foods/aerosol	No	$LD_{50} = 0.03\ \mu m$/person incapacitating	1–12 hr	Hours to a week	Low: <1%	No, but under development	No	Worldwide
Typhoid fever (*Salmonella typhi*)	Food, water; fecal/urine	Rarely	Moderate	7–21 d	Weeks	Moderate (10%)	Yes	Yes	Worldwide

[a] IPPD, intradermal purified protein derivative.
[b] BCG, Bacille Calmette-Guérin.

TABLE 19-2

Characteristics of Vector-Borne Infections Potentially Transmitted in Aircraft

Disease	*Major Vector(s)*	*Person-to-person Spread*	*Infectivity*	*Incubation Period*	*Illness Duration*	*Untreated Lethality*	*Vaccine/Antisera Available?*	*Effective Antibiotics?*	*Common Geographic Location(s)*
Babesiosis (*Babesia* sp)	Ticks	No (transfusable)	High	1 wk–12 mo	Days to months	Low (except if asplenic)	No	Yes	North America, Europe
Bartonellosis (*Bartonella bacilliformis*)	Sand flies	No (transfusable)	High	16–22 d (up to 4 mo)	Days to weeks	High/moderate (10%–90%)	No	No	Peru, Ecuador, and Colombia (600–2800 m ASL)
Dengue fever	Mosquitoes; aerosol	No	High	3–14 d (usually 5–7)	Days to weeks	Low	Experimental	No	Tropics
Viral encephalities									
Eastern equine encephalitis	Mosquitoes; aerosol	No	High: 10–100 organisms	5–10 d	1–3 wk	High	Yes	No	Americas
Russian spring-summer encephalitis	Milk; mosquitoes; aerosol	No	High: 10–100 organisms	8–14 d	Days to months	Moderate	Yes	No	Asia
Venezuelan equine encephalitis	Mosquitoes; aerosol	Low	High: 10–100 organisms	2–6 d	Days to weeks	Low	Yes	No	Americas
Western equine encephalitis	Aerosol	No	High: 10–100 organisms	1–20 d	1–3 wk	Low	Yes	No	Americas
Hanta pulmonary syndrome	Aerosol	No	Assumed moderate	3 d–2 mo (usually 2–4 wk)	9–17 d	High (40%–50%)	No	No	Southwest United States
Hemorrhagic fevers									
Chikungunya	Aerosol	No	High	2–6 d	2 wk	Very low	Experimental	No	Southeast Asia, India
Korean (Hantaan)	Body fluids; aerosol	No	High	4–42 d	Days to weeks	Moderate	Experimental	No	Asia
Lassa	Body fluids; aerosol	Moderate	High	10–14 d	1–4 wk	Low to moderate (1% overall)	No; antisera experimental	Antivirals	Africa
Omsk	Water; aerosol	Rarely	High	3–7 d	7–10 d	Low	Experimental	No	Western Siberia
Leishmaniasis, cutaneous (*Leishmania* and *Viannia* sp)	Sand flies	Rarely	Assumed low	1 wk–mo	Months–1 yr	Low	No	Yes	South and Central America, Asia, Central Africa, Dominican Republic, Mediterranean basin

Leishmaniasis, visceral (*Leishmania* and *Viannia* sp)	Sand flies	Rarely	Assumed low	10 d–2 yr (usually 2–6 mo)	Can be prolonged	High	No	Yes	South and Central America, Asia, Central Africa, Dominican Republic, Mediterranean basin
Lyme disease (*Borrelia burgdorferi*)	Ticks	No (transfusable)	Low	3–32 d (first stage may be asymptomatic)	Weeks to years	Low	No	Yes	North America, Europe, Asia
Malaria (*Plasmodium* sp)	Mosquitoes	No (transfusable)	Low	7–30 d (depends on type and may be delayed)	Attacks: days; recurrences: years	Falciparum high; others low	No	Yes	Localized, but worldwide (see CDC[a] website)
Relapsing fevers (*Borrelia* sp)	Ticks and lice	No	Low	5–15 d (usually 8)	1–10 relapses of 2–9 d of fever with 2–4 d between bouts	Low/moderate (10%)	No	Yes	Localized, but worldwide
Rift Valley fever	Mosquitoes; infected biologicals; aerosol	Low	High	2–5 d	Days to weeks	Low	Yes	No	Africa
Rocky mountain spotted fever (*Rickettsia rickettsii*)	Ticks	No	High	3–14 d	2–3 wk	High (25%)	No	Yes	The United States (April–September)
Tularemia (*Francisella tularensis*)	Mosquitoes, ticks, deerflies; infected biologicals; aerosol	No	High: 10–50 organisms	1–14 d (usually 3–5)	>2 wk	Moderate (10%)	Yes	Yes	North America, Asia, and Europe
Typhus (epidemic)	Lice	No	High	6–16 d	Weeks to months	High	No	Yes	Colder areas; especially during war or famine
Typhus (scrub)	Mites	No	High	4–15 d	6–21 d (usually 10–12)	Usually low; but some strains are 60%	No	Yes	Central, eastern and Southeast Asia, and South Pacific
Yellow fever	Mosquitoes; aerosol	No	High	3–6 d	1–2 wk	High, if jaundiced (50%), rest are moderate	Yes	No	Africa, South and Central America

[a]CDC, Centers for Disease Control and Prevention.

TABLE 19-3

Characteristics of Bioterrorist Agents Potentially Released in Aircraft

Disease	*Major Vector(s)*	*Person-to-person Spread*	*Infectivity*	*Incubation Period*	*Illness Duration*	*Untreated Lethality*	*Vaccine/Antisera Available?*	*Effective Antibiotics?*	*Common Geographic Location(s)*
Anthrax	Deliberate or accidental aerosol	No	Moderate: 8,000–50,000 spores	1–6 d	3–5 d	High (pulmonary)	Aerosol 200 LD_{50} efficacy in monkeys; antisera experimental	Yes, but only effective early	Worldwide
Brucellosis	Deliberate aerosol or in food supply (raw milk)	No	High: 10–100 organisms	5–60 d (usually 1–2 mo)	Weeks to years	Low <5%	No	Yes, but limited effectiveness	Worldwide
Venezuelan equine encephalitis	Mosquitoes; aerosol	Low	High: 10–100 organisms	2–6 d	Days to weeks	Low	Yes	No	Americas
Congo-Crimean	Ticks; body fluids; aerosol	Moderate	High	3–12 d	Days to weeks	High (~50%)	Experimental; antisera in Bulgaria	Yes	Europe, Africa, Central Asia, Middle East
Ebola	Body fluids; aerosol	Moderate	High	7–9 d	2–21 d	Very high (50%–90%)	No	No	Africa
Korean (Hantaan)	Body fluids; aerosol	No	High	4–42 d	Days to weeks	Moderate	Experimental	No	Asia
Plague (pneumonic)	Fleas (rats); aerosol	High	High: 100–500 organisms	2–3 d	1–7 d (usually 2–4 pneumonic)	Very high (~100%)	Yes, but questionably effective for aerosol	Yes	Worldwide
Q fever	Food; aerosol (infected biologicals)	Rarely	High: 1–10 organisms	10–40 d	2–14 d	Low	Yes	Yes	Worldwide
Smallpox	Contact with infected materials; aerosol	High	High: 10–100 organisms	7–17 d (usually 12)	4 wk (usually 1–2)	High	Yes	No	Nowhere

Toxins									
Botulism	Food, water; aerosol	No	$LD_{50} = 0.001\ \mu m/kg$ for Type A	1–5 d	24–72 hr or longer	High	Yes	No	Worldwide
Clostridium perfringens	Food, water; aerosol	No	High	8–12 hr	24 hr	Low	No	No	Worldwide
Staphylococcal enterotoxin B	Foods/aerosol	No	$LD_{50} = 0.03\ \mu m$/person incapacitating	1–12 hr	Hours to a week	Low: <1%	No, but under development	No	Worldwide
Tuberculosis	Aerosol (dust and droplets); milk	Yes	Moderate	4–12 wk for IPPD[a] conversion	Years	Moderate if activated	Yes (BCG[b])	Yes, but lengthy course of multiple drugs	Worldwide
Tularemia	Mosquitoes, ticks, deerflies; infected biologicals; aerosol	No	High: 10–50 organisms	1–14 d (usually 3–5)	>2 wk	Moderate (10%)	Yes	Yes	North America, Asia, and Europe
Typhoid fever	Food, water; fecal/urine	Rarely	Moderate	7–21 d	Weeks	Moderate (10%)	Yes	Yes	Worldwide
Typhus (epidemic)	Lice	No	High	6–16 d	Weeks to months	High	No	Yes	Colder areas; especially during war or famine
Typhus (scrub)	Mites	No	High	4–15 d	6–21 d (usually 10–12)	Usually low; but some strains are 60%	No	Yes	Central, eastern and Southeast Asia, and South Pacific
Yellow fever	Mosquitoes; aerosol	No	High	3–6 d	1–2 wk	High, if jaundiced (50%), rest are moderate	Yes	No	Africa, South and Central America

[a]IPPD, intradermal purified protein derivative.
[b]BCG, Bacille Calmette-Guérin.

TABLE 19-4

Common Presenting Signs or Symptoms of Relevant Infectious Diseases

	Fever	Flu-like Illness	Pharyngitis	Maculopapular Rash	Vesiculopustular Rash	Ulcerative Rash	Ecchymotic Rash	Diarrhea	Jaundice	Stiff Neck	Encephalopathy	Pneumonia/ARDS	Polyarthralgia
Person-to-Person Transmission													
Influenza	X	X	—	—	—	—	—	—	—	—	—	X	—
Plague (pneumonic)	X	—	—	—	—	—	X	—	—	—	X	X	—
Tuberculosis	X	—	—	—	—	—	—	—	—	—	—	X	Rarely
Bioterrorist Agents													
Anthrax (inhalational)	X	Early	—	—	—	—	—	—	—	—	—	X	—
Brucellosis	X	X	—	—	—	—	—	—	—	—	—	—	—
Plague (pneumonic)	X	—	—	—	—	—	X	—	—	—	X	X	—
Smallpox	X	X	—	Early	X	—	Rarely	—	—	—	—	—	—
Toxins													
Botulism		—	X	—	—	—	—	—	Rarely	—	—	X	—
Clostridium perfringens	Rarely	—	—	—	—	—	—	—	—	—	—	—	—
Staphylococcal enterotoxin B	Rarely	—	—	—	—	—	—	X	—	—	—	X	—
Typically Foodborne													
Hepatitis A	X	—	—	—	—	—	X	—	—	—	—	—	—
Shigellosis	X	—	—	—	—	—	—	X	—	—	—	—	—
Typhoid fever	X	—	—	X	—	—	—	Rarely		—	—	—	
Typically Vector Transmission													
Dengue fever	X	X	—	X	—	—	X	—	—	—	X	—	—
Encephalidities													
Eastern equine encephalitis	X	—	—	—	—	—	—	—	—	X	X	—	—
Russian spring-summer encephalitis	X	—	—	—	—	—	—	—	—	—	X	—	—
Venezuelan equine encephalitis	X	X	—	—	—	—	—	—	—	X	X	—	—
Western equine encephalitis	X	—	—	—	—	—	—	—	—	X	X	—	—
Hanta pulmonary syndrome	X	—	—	—	—	—	—	—	—	—	—	X	—
Hemorrhagic fevers													
Chikungunya	X	X	—	X	—	—	—	—	—	—	—	—	X
Congo-Crimean	X	—	—	—	—	—	X	—	—	—	—	X	—
Ebola	X	—	X	X	—	—	X	X	X	—	—	—	—
Korean (Hantaan)	X	—	—	—	—	—	X	—	—	—	—	X	—
Lassa	X	—	X	—	—	—	—	X	X	—	X	—	—
Omsk	X	—	—	—	—	—	X	—	—	—	—	X	—
Malaria	Periodic	—	—	—	—	—	—	—	—	—	X	—	—
Relapsing fever	Intermittent	—	—	—	—	—	—	—	—	—	—	—	—
Rift Valley fever	X	X	—	—	—	—	X	—	—	—	Rarely	—	—
Rocky mountain spotted fever	X	—	—	X	—	—	X	—	—	—	—	—	—
Yellow fever	X	—	—	—	—	—	X	—	X	—	—	—	—

ARDS, acute respiratory distress syndrome; X, condition present.

alter the course of a disease and potentially mask common symptoms and signs and/or alter diagnostic tests. Toxic reactions may occur to readily available medicines obtained in unregulated areas, as well as drug fever or other reaction to many formulations. For example, sulfa-based drugs, used for prevention of altitude illness (acetazolamide), malaria treatment (sulfadoxine–pyramethamine), or diarrhea (trimethoprim sulfamethoxazole), may not only cause drug fever or rash but also potentially serious bone marrow suppression. The form and packaging of the tablet, capsule, or suspension obtained may not be readily identifiable using national drug formulary references.

AIRCRAFT AS VECTORS

Disinsection

Although rare instances of malaria-infected mosquitoes being transported to nonendemic areas have been well documented as so-called airport malaria, it seems likely that infectious insects and other potential disease vectors (such as birds infected with avian influenza or the West Nile Virus, or bats, or raccoons infected with rabies) are only rarely transported from one location to another on commercial aircraft. Killing insect vectors in the aircraft cabin before leaving the host nation airport deals with the logical probability of inadvertent transport of these pests (7). These measures actually address flying insects best because the spray is both toxic to flying insects and applied in a manner that would not be effective against crawling insects or small animals.

Only a small number of countries routinely require disinsection, but most reserve the right to do so when they perceive a threat to public health. The WHO and the International Civil Aviation Organization (ICAO) require one of two methods of aircraft disinsection: either spray the cabin with an aerosolized insecticide (usually 2% phenothrin) as the passengers complete the boarding process; or treat the cabin with a residual insecticide while passengers are not on board. There is a third method advanced more recently: spray the cabin with an aerosolized insecticide while passengers are not on board. For more information on ICAO and WHO, see Chapter 28.

As of June 2007, the only countries requiring disinsection while passengers are on board inbound aircraft are China, Cuba, Grenada, India, Kiribati, Madagascar, Seychelles, Trinidad, Tobago, and Uruguay. Countries requiring disinsection, but allowing residual application for inbound flights are Australia, Barbados, Cook Islands, Fiji, Jamaica, and New Zealand. Spraying aerosols while passengers are not on board is allowed by Panama. Several other countries require disinsection on flights only from selected departure locations and/or by season. Current information on disinsection requirements can be found on the Internet (8).

A 1995 WHO report (9) found no risk to health from properly performed disinsection, but did note that some individuals may experience transient discomfort after aerosol treatments. If aerosol disinsection evokes symptoms or other health concerns exist for a particular patient, current information on disinsection requirements can be obtained from any major airlines' headquarters staff.

Air Handling

The circulation of air aboard commercial aircraft is different with engines running or not. At the gate with engines off, ventilation to the passenger cabin is supplied by a ground air conditioning unit, a ground pneumatic source that supplies the air required to run the aircraft environmental control unit (ECU), or an auxiliary power unit (APU) that powers the aircraft ventilation system. There is little circulation and replacement of air during operation of these systems. With engines running, bleed air is used, after cooling and conditioning, for cabin cooling. The distribution system runs the length of the cabin either over the windows or in the midceiling. Air flows to exhaust grills along the sidewalls at floor level so that circulating cabin air enters and leaves at about the same seat row. Airflow is normally reduced during takeoff and landing, but it may also be reduced when parked away from the gate during delays unless provisions are made to supply adequate ventilation (Figure 19-1). It is of note that the U.S. Department of Transportation suggested, "If the ventilation system is not operating, passengers should not stay aboard for long time periods (i.e., >30 minutes)" (10).

Aircraft built before the late 1980s usually do not have recirculating air systems, although some have been modified to do so, and all cabin air is taken from outside. Most modern commercial aircraft recirculate 10% to 50% of the cabin air after mixing it with new bleed air in order to provide higher flow rates and lower costs to condition the air for cabin comfort. During cruise flight, an average of 20 air exchanges per hour are accomplished; various aircraft types vary from 5 to 50 air exchanges each hour (11). On the ground and during takeoff and landing, this may be reduced to one third of that value. Recirculating air is also filtered by high-efficiency particulate air (HEPA) filters that remove particles larger than approximately 0.3 μm on modern aircraft, although effective maintenance and protection from moisture are required for most effective filtration performance. Because most bacteria and viruses that are transmitted through the aerosol route are spread through "droplet nuclei" that are typically larger than 5 μm, they are efficiently filtered by HEPA filters. Even so-called weaponized anthrax spores are rarely less than 0.5 μm and therefore would be effectively filtered by a modern, well-maintained aircraft HEPA filter.

The effective recirculation and filtration system is easily subverted, however, by individual passenger behavior. No amount of air exchanges and filters can protect against open-mouthed coughing and lack of washing of contaminated hands. Simple measures such as using a handkerchief or tissue, and washing hands frequently and before eating, will reduce disease transmission risk significantly. Handling used eating and drinking materials from other passengers in the row during cabin clean up seems an obvious source

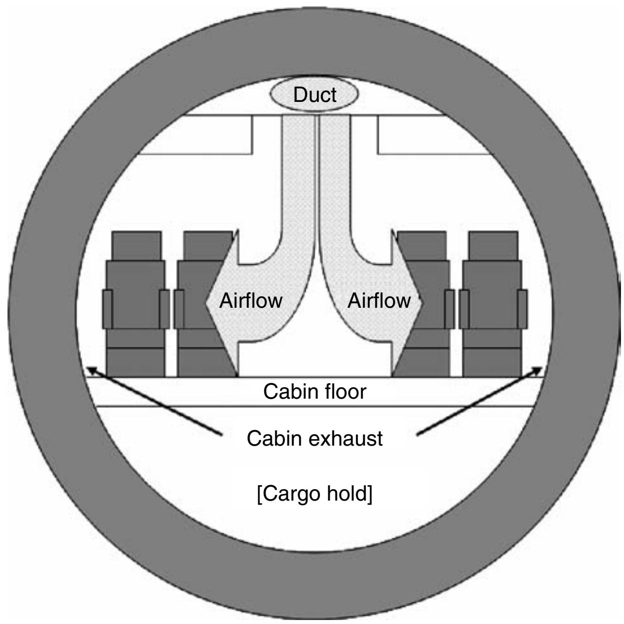


FIGURE 19-1 Schematic of aircraft cabin airflow.

of contamination if hands are not immediately sanitized afterwards. Hand sanitizing agents are effective when used appropriately, but their liquid/gel composition may restrict them from use in the cabin during periods of high terrorist threat. Current information on prohibited items can be found on the Transportation Security Administration (TSA) website (12).

The bottom line is that disease transmission is likely only on flights of more than 8 hours total duration and then only for those sitting within two rows of the infectious passenger. A few highly contagious agents (such as the SARS-associated coronavirus) appear to have been transmitted during flights as brief as 3 hours to passengers several rows away from the index case (9,13). The possibility of more direct contacts among those individuals developing SARS in these situations, however, cannot be totally eliminated. Public health authorities in China and Hong Kong were able to screen patients for fever before boarding aircraft and extensive public education helped minimize additional cases boarding planes. The experience of public health authorities and airlines with SARS actually served as preparation for the looming prospect of pandemic influenza (either an efficiently transmitted mutation of the avian H5N1 strain or a more typical but novel strain). Because influenza is characteristically associated with sudden onset of symptoms, it is possible for someone to board a plane feeling well and become ill during the flight. Influenza can be efficiently transmitted to surrounding passengers but should be filtered by properly functioning HEPA filters. Once pandemic influenza is established, education and screening, along with quarantine measures and follow-up contact information for passengers, will all need to be established. As guidelines are likely to continue to evolve, it will be critical to update practices as per the WHO and CDC websites.

SCIENTIFIC REPORTS OF DISEASE TRANSMISSION

Several infectious diseases have been reported to be transmitted aboard commercial aircraft flights, including SARS, TB, meningitis (detailed in the subsequent text), as well as cholera (14), shigella (15), salmonella (16), influenza (17), and measles (18). Of the reported cases, a majority was food borne illness. Some infections that are potentially transmitted by contact with fellow passengers are discussed in detail in the subsequent text.

Viral Respiratory Diseases

Viral respiratory diseases are among the most common infections in humans, and are easily transmitted through respiratory droplet nuclei coughed or sneezed into the environment, and through contact with surfaces where these droplet nuclei land. It is probable that aircraft (or car, bus, or train) passengers surrounding an infected individual, especially if coughing or sneezing, are exposed. Droplet nuclei, typically 5 μm in diameter, are filtered by aircraft HEPA filters. Uninfected individuals, generally within approximately 1 m of an infected individual, may be infected by inhaling droplets suspended in the air. Many respiratory viruses, in the absence of ultraviolet (UV) light, can survive on surfaces for hours to days and can be transmitted by hands to other individuals. Although most viral respiratory infections are relatively mild, two important exceptions must be considered: SARS coronavirus and influenza. The outbreak of SARS in Asia and subsequent spread to Toronto, Canada by air travelers highlighted the role of aircraft in transporting passengers who are incubating an illness, or are mildly ill, to another nation, but also demonstrated transmission of a dangerous viral respiratory infection during flight. Although only four cases of SARS transmission are suspected to have occurred during flight, the significant morbidity and mortality of cases led both the WHO (19) and the U.S. CDC (20) to develop guidelines for aircraft travel if SARS occurs. Current plans for response to a pandemic viral outbreak can be found on the ICAO (21) and International Air Transport Association (IATA) (22) websites.

The recommendations currently promulgated for SARS are basic guidance for infectious disease outbreaks and include the following:

1. Screening patients before boarding by checking for fever and asking questions about any symptoms of cough or fever
2. Separating passengers who become ill during flight, as much as possible, from other passengers and giving them a mask to wear to minimize droplet nuclei (if they cannot wear a mask they should be instructed to cough or sneeze into tissues); careful hand washing is critical
3. Requiring staff directly caring for ill passengers to wear masks and use gloves for handling any tissues, secretions, among others from ill passengers; careful hand washing is critical

4. Notifying quarantine stations while the flight is *en route* so that potentially infected passengers can be isolated and observed on arrival
5. Observing passengers and crew on the aircraft for evidence of disease for 10 days after arrival and instructing them to immediately seek medical attention if they develop symptoms

Pandemic influenza is likely to be much more easily transmissible than SARS and will require similar vigilance and measures on board. Travel restrictions from infected areas may be more restrictive than during SARS.

Tuberculosis

A flurry of papers reached varied conclusions, but in summary, it appears that person-to-person spread is difficult even in the close confines of tourist class cabins. Investigations have examined possible transmission of *Mycobacterium tuberculosis* on airplanes involving at least seven different persons with active disease (23–29). One of these investigations documented transmission of *M. tuberculosis* from a symptomatic index passenger to six passengers with no other risk factors, sitting in the same section of a commercial aircraft during a long flight (>8 hours) (19). However, those documented as exposed did not develop active disease. The remainder of the studies found no significant risk to passengers or aircrew. This is probably due to the fact that *M. tuberculosis* bacteria, although 0.5 to 1.0 μm in size, are most efficiently spread through droplet nuclei of approximately 5 μm. These particle sizes are completely removed through HEPA filtration of cabin air. Therefore, only direct inhalation of droplet nuclei, before filtration by cabin filters, is associated with significant TB exposure.

The WHO recommends the following for medical authorities concerning TB and air transportation: (a) persons with infectious TB should not travel until they become noninfectious (~2 weeks after beginning an appropriate drug treatment regimen and sputum cultures have become negative), (b) in a patient with suspected or confirmed active TB who has traveled by air during the preceding 3 months, public health authorities should be informed immediately including details of the travel history, and (c) public health authorities should promptly contact the airline company if the patient with known infectious TB has traveled on a flight of at least 8 hours duration during the previous 3 months. Unfortunately, these conservative recommendations, critical to prevent the rare occurrence of aircraft associated transmission of TB, are associated with considerable media attention and often unduly scare passengers despite the fact that it is highly unlikely they have been infected during their flight. Even with rarely documented occurrences of TB infection [i.e., purified protein derivative (PPD) conversion with no active disease] acquired during flights, there has not been documentation of any manifest TB disease in those who were infected (30).

Meningitis

Approximately 12 cases of confirmed meningococcal disease are reported each year to the CDC in which the index patient was on an international flight during the contagious period. The diagnosis is almost never made in transit. As for all contagious diseases, the decision to prescribe antibiotic prophylaxis should be based on (a) the risk of transmission, (b) the difficulty in identifying and notifying passengers affected, and (c) the potential severity of illness. For flights longer than 8 hours, passengers seated directly next to the index patient are more likely to be directly exposed to the patient's oral secretions and are therefore probably at higher risk than those seated farther from the index patient. In the absence of data regarding elevated risk among other passengers, antimicrobial chemoprophylaxis should be considered for those passengers seated directly next to the index patient. Given the increased frequency of ground delays before takeoff and after landing, one needs to count the total time and not just the air transit time; the more than 8-hour time period should include the total time from when the passengers are seated for takeoff until they disembark. For bacterial meningitis, there are no documented cases of secondary disease among passengers.

The CDC, in conjunction with the Council of State and Territorial Epidemiologists, recommends the following actions for meningococcal exposures: (a) household members traveling with the index patient, as well as persons traveling with the index patient who have prolonged close contact (e.g., roommates, members of the same sports team), should be identified, and the need for antimicrobial chemoprophylaxis evaluated; (b) the health department from the state where the patient resides should be contacted promptly to facilitate antimicrobial chemoprophylaxis of household members, day care center contacts, and other possible close contacts; (c) antimicrobial chemoprophylaxis should be considered for passengers who have had direct contact with respiratory secretions from the index patient and passengers seated directly next to the index patient on prolonged flights (>8 hours); (d) CDC and state health departments should enhance surveillance for secondary cases associated with airline travel because identification of such cases would alter these recommendations; and (e) airlines should be responsible for maintaining a passenger manifest to aid in identification of passengers at risk for secondary infections. The CDC should work with airlines to identify the location of potentially exposed passengers. With the assistance of the airline, the CDC should identify the states where these passengers reside and contact the appropriate state and local health officials. The state or local health department will then contact passengers as and when necessary.

There is a need for more systematic collection of data on the risk of disease transmission to passenger contacts in order to provide a better basis for public health recommendations (31). At least one recent investigation demonstrated that the only significant effect of air travel bans is likely to be delay of temporal spread of disease, because air travel restrictions after September 11, 2001 in the

United States were associated only with delays in the spread of seasonal influenza viruses (32).

SPACECRAFT ENVIRONMENTS

Of course, the spread of disease aboard space vehicles has been recognized as a problem for off-planet travel since the beginning of the space program. Both the spread from one infectious astronaut to fellow crewmembers and the potential for alien organisms to be brought back to earth and its immunologically *naïve* population have been the subject of elaborate plans and procedures. Last minute changes in crew due to emerging illness or even exposure to infectious diseases in the critical preflight period upset several flights, and the in-flight febrile urinary tract infection of astronaut Fred W. Haise Jr. made the aborted Apollo 13 flight even more memorable than it would have been otherwise. In addition, prime crewmember Thomas K. Mattingly had been exposed to German measles (medical tests revealed that he lacked antibodies and might not be immune), and Jack Swigert replaced Mattingly only days before the launch. On other flights, returning astronauts—and later their moon samples—were isolated immediately upon postflight recovery to reduce the likelihood of bringing an unknown disease back to earth. After the Apollo 11 mission, the astronauts were held in an isolation trailer (Figure 19-2) for 3 weeks, and a surveillance program was conducted among the personnel working with lunar material (33).

More recent space experience has demonstrated that biofilms of bacteria also form in space and the microgravity conditions appear to alter some of their characteristics. *Escherichia coli* form biofilms more readily under simulated spaceflight conditions than do their counterparts grown under ordinary gravity. Because of the evidence that the Mir space station was heavily colonized by biofilms, this finding could well be applicable to other bacteria. On Mir, severe biofouling damaged quartz windows and corroded various metal surfaces, thereby contributing to a shortened useful lifetime of this station (34). After implementing potential countermeasures to biofilms on the International Space Station (ISS), a study of the ISS environment yielded 12 bacterial strains from the ISS water system. These bacteria consisted of common strains, and colony-forming unit densities were below the usual minimum number required to cause illness. These data indicate that countermeasures based on lessons learned from previous missions have been effective (35).

FIGURE 19-2 Apollo 11 Mobile Quarantine Facility. The Apollo 11 crewmen, still under a 21-day quarantine, are greeted by their wives as they arrive at Ellington Air Force Base after a flight aboard a U.S. Air Force C141 transport from Hawaii. Looking through the window of the Mobile Quarantine Facility are (left to right) Astronauts Neil Armstrong, Edwin Aldrin Jr, and Michael Collins. The wives are (left to right) Mrs. Pat Collins, Mrs. Jan Armstrong, and Mrs. Jean Aldrin.

INTENTIONAL EXPOSURES

Currently, the ability of our international travel system to rapidly bring a passenger with an incubating, serious disease into a crowded cabin, a crowded airport, and a *naïve* population is a serious concern. The potential for an aircraft to transport disease vectors to a new location, where they and their imported disease can also thrive, is an international threat. Moreover, there is concern that someone or some group will use the forced contact of transportation hubs and passenger cabins to purposefully infect unsuspecting thousands and spread a new plague around the world efficiently and effectively.

The spread of spores or other fomites aboard aircraft would be difficult due to air handling discussed earlier. Contamination would likely be limited to small volumes surrounding the exposure site, although walking through the aircraft, whereas dispersing an agent would result in large volumes of potential contamination. Contamination of foodstuffs is of limited effect in this era of prepackaged snack foods, although open water containers offer a potential source of pathogen dispersal.

Decisions to produce smallpox vaccines again were based, in part, on a fear that the disease could be reintroduced into a population with vanishing immunity to the disease. The toll in death and disability would be enormous. A new smallpox vaccine containing live vaccinia virus is now produced in cell cultures by modern vaccine production techniques (36). Demonstration programs to administer the vaccine to health care workers and others as part of Homeland Security in the United States met with varying degrees of acceptance, but relatively few serious complications have been reported (37). We can only hope that the vaccine will never again have to be used among the general population.

CHALLENGES

Innovative techniques, and perhaps improved technology solutions, will be needed to effectively and efficiently screen passengers for infectious disease before boarding commercial aircraft. The SARS outbreak resulted in screening of passengers by infrared sensors in Asia to ascertain who had fever and therefore needed additional questioning. Additional sensor technology evolution hopefully will yield equipment that is well tolerated by the traveling public in terms of both accuracy and nonintrusiveness. During serious communicable disease outbreaks, or possibly during future high-risk periods involving serious infectious disease threats (e.g., pandemic influenza [38]), some face-to-face screening may also need to be performed at airports. Experience with acceptance of decontamination measures imposed on debarkation from areas where foot-and-mouth disease was prevalent, and the requirement for liquids to be placed in small plastic bags for security checks, indicate that the public can tolerate significant intrusions if there is a perceived threat present.

Epidemiologic investigation of cases of serious infections must include detailed travel histories, coordinated with airlines as needed to identify contacts, if a true picture of the implications to others of an index infectious case is to be understood when there has been travel during the relevant communicability period. Travelers need to understand that sitting in an aircraft does not excuse one from the necessities of personal hygiene to reduce the possibilities of disease transmission both to and from fellow passengers.

The globalization of commerce has resulted in a rapid increase in travel especially by air. This dramatically increases the opportunities for diseases to be passed to others while symptoms have not yet appeared or while traveling when ill due to job pressures. The high density of travelers aboard aircraft not only presents an opportunity for aggressive organisms but also for the intentional transmission of disease. Serious disease outbreaks facilitated by air travel are likely to occur in the coming years. Practitioners of aerospace medicine must remain aware and knowledgeable of the characteristics of likely diseases if they are to detect outbreaks early enough to effectively interrupt them.

RECOMMENDED READINGS

Textbooks

Centers for Disease Control (CDC). *Health information for international travel, 2005–2006*. New Orleans: Claitor's Law Books and Publishing Division, 2005.

Gorbach SL, Bartlett JG, Blacklow NR, eds. *Infectious diseases*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2004.

Guerrant RL, Walker PH, Weller PF, eds. *Tropical infectious diseases: principles, pathogens, and practice*, 2nd ed. Philadelphia: Churchill Livingstone, 2006.

Heymann DL, ed. *Control of communicable diseases manual*, 18th ed. Washington, DC: American Public Health Association, 2004 (with 2006 update).

Mandell GL, Bennett JE, Dolin R, (eds). *Mandell, Douglas, and Bennett's principles and practice of infectious diseases*, 5th ed. Philadelphia: Churchill Livingstone, 2000.

Nelson KE, Williams CM, eds. *Infectious disease epidemiology: theory and practice*, 2nd ed. Boston: Jones & Bartlett Publishers, 2007.

Pickering LK, ed. *2006 report of the Committee on Infectious Diseases (Red Book Report of the Committee on Infectious Diseases)*, 27th ed. Elk Grove: American Academy of Pediatrics, 2006.

Schlossberg D, ed. *Current therapy of infectious disease*, 2nd ed. St Louis: Mosby, 2001

Strickland GT, ed. *Hunter's tropical medicine*, 8th ed. Philadelphia: WB Saunders, 2000.

World Wide Web Sites

Centers for Disease Control & Prevention–National Center for Infectious Diseases Travelers' Health. http://www.cdc.gov/travel/reference.htm, updated 13 November 2006, accessed 7 July 2007.

Centers for Disease Control & Prevention–The Yellow Book - Health Information for International Travel, 2005–2006. *An In-depth Travel Reference Book Published Biennially*. http://wwwn.cdc.gov/travel/contentYellowBook.aspx, updated 27 June 2007, accessed 7 July 2007.

The Horn of Africa Network for Monitoring Antimalarial Treatment. For extensive malaria links: http://www.hanmat.org/links.htm, updated 18 December 2006, accessed 7 July 2007.

Karolinska Institute. For extensive parasitic disease information: http://www.mic.ki.se/Diseases/C03.html. Stockholm, Sweden: Karolinska Institute, updated 26 June 2007, accessed 7 July 2007.

Centers for Disease Control & Prevention. For CDC publications and data files: http://www.cdc.gov/publications.htm. Atlanta: CDC, updated 26 April 2007, accessed 7 July 2007.

Centers for Disease Control & Prevention. For CDC traveler's health information on specific areas of the world: http://www.cdc.gov/travel/destinat.htm, Atlanta: CDC, updated 11 July 2006, accessed 7 July 2007.

American Medical Association. For articles and links on emerging infectious diseases: http://www.ama-assn.org/ama/pub/category/1797.html. Chicago: American Medical Association, updated 27 June 2005, accessed 7 July 2007.

Centers for Disease Control & Prevention–and the Journal of Emerging Infectious Diseases, http://www.cdc.gov/ncidod/eid/index.htm. Atlanta: published by the CDC, updated 29 June 2007, accessed 7 July 2007.

Centers for Disease Control & Prevention. *Emerging infectious disease* resource links from the CDC, http://www.cdc.gov/ncidod/id_links.htm, updated 20 June 2006, accessed 7 July 2007.

Centers for Disease Control & Prevention. *For patient oriented fact sheets and other information on a host of diseases*. http://www.cdc.gov/health/diseases.htm. Atlanta: CDC, updated 19 April 2007, accessed 7 July 2007.

For information on various infectious agents communicated by foodstuffs, see *The food borne pathogenic microorganisms and natural toxins handbook*. http://vm.cfsan.fda.gov/~mow/intro.html. Washington DC: United States Food and Drug Administration, The Center for Food Safety and Applied Nutrition, updated 25 April 2006, accessed 7 July 2007.

World Health Organization. For information on International Travel health requirements and vaccinations as well as travel health advice from the World Health Organization. http://www.who.int/ith/en/, accessed 7 July 2007.

REFERENCES

1. Richard Thomas. For a detailed discussion of the role of trade in spreading the plague, see http://www.american.edu/projects/mandala/TED/BUBONIC.HTM, dated May 1997, accessed 7 July 2007.
2. Garrett L. *The coming plague*. New York: Penguin Books, 1995: 563–570.
3. United States Department of Health and Human Services. *Managing travel-related risk of disease transmission*. www.hhs.gov/pandemicflu/plan/sup9.html, last updated 15 May 2007, accessed 7 July 2007.

4. Heymann DL, ed. *Control of communicable diseases manual*, 18th ed. Washington, DC: American Public Health Association, ISBN 0-87553-034-6, softcover, 2004 (with 2006 update).
5. Gilbert DN, Moellering RC, Eliopoulis GM. *The sanford guide to antimicrobial therapy 2006*, 36th ed. Hyde Park: Antimicrobial Therapy, Inc, 2006.
6. Looke DFM, Robson JMB. Infections in the Returned Traveller. *Med J Aust* 2002;177(4):212–219; Also on Internet site: http://www.mja.com.au/public/issues/177_04_190802/loo10413_fm.html, accessed 7 July 2007.
7. Rayman RB. Aircraft disinsection. *Aviat Space Environ Med* 2006; 77:733–736.
8. Konheim A. *Aircraft disinsection requirements*. Internet site: http://ostpxweb.dot.gov/policy/safetyenergyenv/disinsection.htm, accessed 7 July 2007.
9. World Health Organization (WHO). *Report of the Informal Consultation on Aircraft Disinsection*. WHO: Geneva, Switzerland, Nov 1995.
10. Committee on Air Quality in Passenger Cabins of Commercial Aircraft (National Research Council). *The airliner cabin and the health of passengers and crew*. Washington, DC: National Academy Press, 2002.
11. Mangili M, Gendreau MA. Transmission of infectious diseases during commercial air travel. *Lancet* 2005;365:989–996.
12. United States Transportation Security Administration. *Permitted and prohibited items: air travel*. http://www.tsa.gov/travelers/airtravel/prohibited/permitted-prohibited-items.shtm. Accessed 7 July 2007.
13. Nagda NL, Fortmann RC, Koontz MD, et al. *Airliner cabin environment: contaminant measurements, health risks and mitigation options*, Report number DOT-P-15-89-5. Washington, DC: US Department of Transportation, 1989.
14. Eberhart-Phillips J, Besser RE, Tormey MP, et al. An outbreak of cholera from food served on an international aircraft. *Epidemiol Infect* 1996;116:9–13.
15. Hedberg CW, Levine WC, White KE, et al. An international food borne outbreak of shigellosis associated with a commercial airline. *JAMA* 1992;268:3208–3212.
16. Tauxe RV, Tormey MP, Mascola L, et al. Salmonellosis outbreak on transatlantic flights; food borne illness on aircraft: 1947–1984. *Am J Epidemiol* 1987;125:150–157.
17. Moser MR, Bender TR, Margolis HS, et al. An outbreak of influenza aboard a commercial airliner. *Am J Epidemiol* 1979;110:1–6.
18. Amler RW, Bloch AB, Orenstein WA, et al. Imported measles in the United States. *JAMA* 1982;248:2219–2233.
19. WHO. *Summary of SARS and Air Travel*. www.who.int/csr/sars/travel/airtravel/en/print.html, accessed 7 July 2007.
20. CDC, *Guidance about SARS for Airline Flight Crews, Cargo and Cleaning Personnel, and Personnel Interacting with Arriving Passengers*, Centers for Disease Control and Prevention, May 2005, http://www.cdc.gov/ncidod/sars/airpersonnel.htm, accessed 7 July 2007.
21. International Civil Aviation Organization. *Aviation medicine section*. http://www.icao.int/icao/en/med/medFAQ_en.html#health, accessed 7 July 2007.
22. International Air Transport Association. *Emergency response plan: public health emergency*. http://www.iata.org/NR/rdonlyres/1D412DF9-289B-4508-BE9D-A57C4A84F103/0/AirlinesERPChecklists_V1_Nov30.pdf accessed 7 July 2007.
23. Driver CR, Valway SE, Morgan WM, et al. Transmission of M. tuberculosis associated with air travel. *JAMA* 1994;272:1031–1035.
24. McFarland JW, Hickman C, Osterholm M, et al. Exposure to Mycobacterium tuberculosis during air travel. *Lancet* 1993;342: 112–113.
25. CDC. Exposure of passengers and flight crew to Mycobacterium tuberculosis on commercial aircraft. *MMWR Morb Mortal Wkly Rep* 1992–1995;44:137–140.
26. Miller MA, Valway SE, Onorato IM. Tuberculosis risk after exposure on airplanes. *Tubercule Lung Dis* 1996;77:414–419.
27. Moore M, Fleming KS, Sands L. A passenger with pulmonary/laryngeal tuberculosis: no evidence of transmission on two short flights. *Aviation Space Environ Med* 1996;67:1097–1110.
28. Kenyon TA, Valway SE, Ihle WW, et al. Transmission of multi-drug resistant *Mycobacterium tuberculosis* during a long airplane flight. *N Engl J Med* 1996;334:933–938.
29. WHO. *Tuberculosis and air travel: guidelines for prevention and control*. World Health Organization, 1998, http://www.who.int/inf-pr-1998/en/pr98-96.html accessed 7 July 2007.
30. WHO. *International travel and health 2007*. World Health Organization, 2007. http://www.who.int/ith/en/, accessed 7 July 2007.
31. Riley LK. Bacterial meningitis exposure during an international flight: lessons for communicable pathogens. *Aviat Space Environ Med* 2006;77:758–760.
32. Brownstein JS, Wolfe CJ, Mandl KD. Empirical evidence for the effect of airline travel on inter-regional influenza spread in the United States. *PLoS Med* 2006;3:e401.
33. Brooks GF. Health surveillance of lunar receiving laboratory personnel during the apollo 11 quarantine period. *Am J Publ Hlth* 1970;60:1956–1959.
34. Matin A, Lynch SV. Investigating the threat of bacteria grown in space. *ASM News* 2005;70:235–240.
35. NASA. *Environmental monitoring of the international space station*. http://exploration.nasa.gov/programs/station/Environmental-Monitoring.html, *updated 6 June 2007, accessed 7 July* 2007.
36. CDC. *Smallpox vaccination: information for health professionals*. http://www.bt.cdc.gov/agent/smallpox/vaccination, accessed 7 July 2007.
37. Schwartz B, Lebwohl M. Complications of the smallpox vaccine. *Int J Derm* 2005;44:289–292.
38. Evans A, Finkelstein S, Singh J. Pandemic influenza: a note on international planning to reduce the risk from international air transport. *Aviat Space Environ Med* 2006;77:974–976.

CHAPTER 20

Dental Considerations in Aerospace Medicine

William M. Morlang, II*

"Dentistry's Growth in the Last Quarter Century has Reached Aerospace Medicine." Dental practice has changed dramatically over the last 25 years with the current focus being on prevention (1). Additionally, advanced equipment, instrumentation, techniques, and materials have made new options possible when treatment is required. With this growth emerged many subspecialty areas. Aerospace medicine physicians seeking consultation from dental subspecialists, and aviators seeking quality dental care in general, should consider dentists with advanced credentials (Table 20-1).

REACHING AEROSPACE MEDICINE

Dentistry plays two major roles in aerospace medicine. First, dentistry contributes to the aviator's overall wellness. An aviator's physical standards must include his or her oral and dental health status. Through timely and appropriate oral and maxillofacial examination and diagnostic radiology, dentists are able to assess an aviator while his or her disease is in an early stage.

To further promote this wellness, a positive and proactive relationship must exist between the aviator, the dentist, and the aerospace medicine physician. This professional relationship, which includes keen professional communications about the aviator, must be fostered by all more aggressively. The dentist and physician must communicate regarding the dentist's treatment of and medication prescriptions for their mutual patient. The military health care delivery model provides an example for the civilian community to emulate to promote such communication, although the Health Insurance Portability and Accountability Act (HIPAA) has several exceptions for the disclosure of protected health information among covered entities to make such communication usually feasible (2).

Second, forensic odontology often has the lead role in the identification of deceased aviators and other fatalities after aircraft mishaps, particularly so given the destruction of impact forces and associated fires. Genetic identification of human remains can be done using either nuclear or mitochondrial deoxyribonucleic acid (DNA). Nuclear DNA

TABLE 20-1

Certifying Boards and Professional Organizations

Board	*Organization*
American Board of Endodontics	Academy of General Dentistry
American Board of Forensic Odontology	American Academy of Forensic Sciences
American Board of General Dentistry	American College of Dentists
American Board of Oral and Maxillofacial Pathology	International College of Dentists
American Board of Oral and Maxillofacial Radiology	—
American Board of Oral and Maxillofacial Surgery	—
American Board of Orthodontics	—
American Board of Pediatric Dentistry	—
American Board of Periodontology	—
American Board of Prosthodontics	—
American Board of Dental Public Health	—

*Dr. Morlang is certified by the American Board of Forensic Odontology. He is a Consultant in Forensic Odontology to the Armed Forces Institute of Pathology. Dr. Morlang is an Adjunct Associate Professor at Tufts University's School of Dental Medicine. He is a Fellow of the Academies of General Dentistry and Forensic Sciences, the American College of Dentists, and the International College of Dentists. Dr. Morlang served in the United States Air Force for thirty years, attaining the rank of Colonel.

deteriorates rapidly in an aircraft mishap environment, whereas mitochondrial DNA is more stable and therefore used more frequently for forensic identifications. Forensic dental identification of a deceased is a fraction of the cost compared to DNA identification. It is also weeks to months faster.

An invaluable asset to forensic odontology has been the military's repository for duplicate panoral dental radiographs of its military members. Unfortunately, no new dental radiographs are being added currently to this repository. Instead, United States military members' DNA is being stored in a repository, believed to now have over 5 million specimens. This author maintains that the military's dental radiograph repository should be continued.

On the civilian side, it would be prudent for civilian aviators to place a full-mouth dental radiographic series, a fingerprint card, a footprint card, and a dried blood specimen in their private safety deposit boxes. This could be accomplished with the assistance of civilian dentists, medical laboratories, physicians, and law enforcement agencies.

The forensic dental identification process itself is detailed and beyond this chapter's scope, so it turns now to focus on how dentistry plays a major role in an aviator's overall wellness.

DENTAL RECORDS

Quality record documentation and sound data management are critical to reliable practice management. They are also allies in malpractice prevention and legal defense at all professional levels. Dental records can be in either paper or electronic format. Electronic format is growing in popularity now because of its ease to incorporate digital dental radiographs.

An aviator's dental record must be uniquely marked in the dental practice so that all staff know that they are caring for a patient with special requirements. All health care providers must be acutely aware also of aviators who are in sensitive duty programs. Dental records of these persons must also be uniquely marked for recognition. Treatment notification procedures defined in such sensitive duty programs must be followed, without exception.

Quality record documentation enhances proper oral diagnosis, treatment planning, and communication between dentists and aerospace medicine physicians. The United States military services have a straightforward standardization of dental records; however, in civilian practice, a wide diversity of dental forms, charting systems, tooth numbering systems, and abbreviations exists. Attempts, largely driven by the insurance industry, to standardize documentation in civilian dental practice have been only somewhat successful. Nonetheless, an aviator's dental record should reflect recognized charting methods and symbols, self-intuitive abbreviations, and an accepted tooth numbering system.

Tooth numbering systems are illustrated in most dental anatomy textbooks. The three major systems are *Palmer Notation, World Dental Federation Notation* of the Fédération Dentaire Internationale (FDI), and *Universal Numbering System*. The *Universal Numbering System* assigns each tooth a number, 1 through 32. The sequence begins with tooth number 1—the maxillary right third molar—and continues sequentially around the maxilla to number 16—the maxillary left third molar. The sequence then shifts to the mandibular arch on the left side with tooth number 17—the mandibular left third molar—and continues sequentially around the mandible ending with tooth number 32—the mandibular right third molar. The *Universal Numbering System* is preferred because it is compatible with the *WinID3* forensic identification computer system. *WinID3* is presently the premier database program that filters and sorts antemortem and postmortem medical, dental, anthropological, and digital radiographic data to assist in the forensic identification of mass disaster fatalities.

In addition to those elements of charting required by state law, a dentist should be sure to chart the following about aviators: privacy compliance, informed consent, all existing dental restorations, missing teeth, prosthodontic/orthodontic appliances, pathology if noted, treatment plans, treatment delivered, medication prescribed, along with communications with the aviator and aerospace medicine physician. A polished dental practice will also provide the aviator with care instructions delivered both by speaking and in writing.

If time is taken to document in a quality fashion, then similar time should be taken to preserve that important data. Simply stated, backup of electronically stored dental record data is paramount. Further, movement of original dental records into combat zones or otherwise "in harm's way" should first be considered carefully to protect forensic antemortem data that might be required for postmortem identification. Aviators should not transport their own original dental records on the same aircraft that they are flying.

DENTAL RADIOLOGY

The field of oral and maxillofacial radiology has excelled dramatically in recent years (3). Modern digital dental radiology systems reduce treatment time, provide almost instant results, afford rapid quality review, and reduce radiation exposure.

At a minimum, either a full-mouth series of periapical dental radiographs or a panoral radiograph is essential to have in an aviator's dental record. The aviator's record must contain an original radiographic series noted in the preceding text and be augmented with annual bitewing-type radiographs, or as needed, periapical dental radiographs. A new full-mouth radiographic series should be taken every 5 years (or sooner, if significant dental treatment has altered the aviator's "dental radiographic profile").

ORAL DIAGNOSIS AND TREATMENT PLANNING

Prevention and proper diagnosis are the keys to superior oral health (4,5). The level of oral examination should be commensurate with the aviator's indicated physical examination.

An initial and comprehensive type I examination should include a full-mouth radiographic series, an extensive dental examination, a quality periodontal examination, a complete intraoral soft tissue examination, a palpation of appropriate head and neck lymph node sites, a review of the aviator's current health history and medications, and a blood pressure screening. Follow-up visits after that may include type II or type III examinations. A type II examination substitutes bitewing-type radiographs for the full-mouth radiographic series. A type III examination requires no new radiographs. Necessity for such follow-up is within the dentist's discretion, unless otherwise required by agency guideline.

At a minimum, the aviator should have at least a type II examination and oral prophylaxis annually. Aviators with histories of significant dental problems should be seen every 6 months. Preventive dental counseling, frequent tooth brushing with fluoride toothpaste, flossing, and fluoridated water consumption are beneficial to maintaining superior oral health (6). Planning for extensive dental treatment for an aviator should be coordinated with his or her aerospace medicine physician before commencement.

RESTORATIVE DENTISTRY

Generally, dental restorations can be of composite material in anterior teeth and of filled composite material or amalgam in posterior teeth (7). The American Dental Association (ADA) considers dental amalgam (silver filling) to be affordable, durable, and both viable and safe for patients with dental problems (8). Therefore, amalgam may well last longer than most composites and tends to prevent recurrent dental decay.

As suggested in the beginning of this chapter, dentistry now offers many new options for treatment (9). For tooth restorations, these include new, stronger composite materials that can be bonded to tooth material especially in posterior teeth and new techniques involving prosthetic facings, which have opened the boutique door for cosmetic veneers (10). Although gaining in popularity among consumers, some cosmetic dentistry techniques often result in a "cut down" of the facial surface of anterior teeth for the placement of prosthetic facings (aesthetic veneers). Such dentists should employ techniques that minimize the risk that an aviator's veneer might become dislodged in flight with possible resulting pain or aspiration. Great care must also be taken to avoid pulpal involvement.

ENDODONTICS AND BARODONTALGIA

Dental examination is warranted when an aviator has sensitivity to thermal change, lingering discomfort, swelling of oral soft tissues, oral suppurative discharge, or dental pain (barodontalgia) especially when it is spontaneous or arises when climbing to altitude.

Barodontalgia can be debilitating to aviators and may contribute to lack of attention, difficulty in communication, or loss of situational awareness. Sometimes, the specific tooth associated with barodontalgia is difficult to identify. In those cases, percussion of teeth or regional local anesthesia performed by the dentist in an altitude chamber while climbing to 10,000 ft is helpful to diagnosis. Of note, maxillary sinus conditions sometimes project dental pain because of the close association of maxillary bicuspid and molar root tips to the floor of the maxillary sinus.

The treatment of dental pulpal disease, a periapical abscess, or barodontalgia usually from severely fractured teeth is generally accomplished by root canal therapy or endodontics (11,12). Instrumented and treated root canals are usually filled with a plastic-type material or silver points and cement. Some forms of endodontic treatment can be done in one sitting. More commonly, root canal therapy is done in multiple sittings. On some occasions, periapical surgery is required to remove localized and walled-off infection in the bone. It is wise for aviators not to fly during the period when the pulp chamber remains unfilled (usually during the first two sittings).

ORAL AND MAXILLOFACIAL SURGERY

This specialty, shared by physicians and dentists, affords a wide range of treatment including tooth extraction, surgical removal of impacted teeth, soft tissue and osseous surgery, tumor excision, treatment of head/neck trauma, treatment of facial fractures, and osteotomies for orthodontic or cosmetic reasons (13–15). Few aviators undergo osteotomies because of the lengthy no-fly period after surgery. Aviators should not fly while most multisitting oral surgery procedures are ongoing. They should also not fly for at least 72 hours after the final, postoperative treatment and discontinuation of most medications.

PERIODONTICS

This specialty treats diseases of the teeth's supporting structure. Long-term poor oral hygiene results in plaque formation and dental calculus buildup in the dental sulcus. This results in an increase in depth of the sulcus and periodontal pockets, periodontal abscess, and alveolar bone loss. Normal adult sulcus depth is approximately 4 mm (16). As this depth increases, pockets form where the patient is unable to clean. Infection sets in and tissue and bone are damaged. Periodontists treat early pockets with subgingival curettage to clean the area and to create shrinkage. If the pocket depth remains at a level where the patient is unable to maintain the area, periodontal surgery is indicated.

In this surgery, the diseased pocket wall is eliminated and the gingival attachment is lowered. Periodontists place periodontal packs to postoperatively protect this surgical area. This pack acts as a template, or form, under which healing occurs. Gingival grafts and bone grafts are not uncommon. Each also requires placement of a periodontal pack. These packs are changed at least weekly until adequate healing has taken place. These packs might interfere with clear speech and could become dislodged. Most periodontal surgery patients are on analgesics and antibiotics, and probably should not fly until cleared by the periodontist and aerospace medicine physician because of the possible risks of pain, bleeding, and periodontal pack dislodgment with potential aspiration thereof. Such occurrences might result in an aviator's lack of attention, airway obstruction, difficulty in communication, or reduced situational awareness.

PROSTHODONTICS

Prosthodontists replace missing teeth with fixed bridges with attached pontics (artificial teeth), implants, removable partial dentures, or full dentures (17–19). Prosthesis dislodgment, aspiration of the prosthesis, and communication problems are major concerns for aviators. Overall, dentists must use great care in constructing, placing, and cementing both individual and temporary crowns to avoid dislodgment and aspiration.

Few active aviators wear full dentures. In contrast, bilateral removable partial dentures are more common. Unilateral, removable, partial dentures should be discouraged for aviators because they might be easily dislodged. Fixed crown and bridge prostheses are preferable for them; however, a *Maryland Bridge* should be avoided because of possible dislodgment. The *Maryland Bridge* is a three-unit anterior fixed bridge that replaces a missing tooth with a pontic. In this case, the abutment teeth supporting the pontic are prepared with inlay restorations instead of full-coverage crowns. The retentive quality of inlays is less than that of full crowns.

Most state laws require identification of dental prosthetic appliances, so dentists should permanently mark the aviator's name in his or her dentures. This marking will also assist forensic odontologists in the identification process in the event of an aircraft mishap.

Of interest, for aviators involved with high-performance fighter aircraft or space flight, some prosthodontists can take extraoral impressions to construct models used in the fabrication of custom oxygen masks, helmet liners, and urine collection devices. Meanwhile, some maxillofacial prosthodontists have superb skills to make facial prostheses for aviators injured in mishaps or disfigured after tumor removal. Artificial eyes, noses, ears, and tissue prostheses—often secured by magnets—are some prosthodontists' common creations (20).

ORTHODONTICS

Wearing a flight oxygen mask is somewhat uncomfortable while undergoing orthodontic care, but adult orthodontic treatment for aviators is possible. However, orthodontic treatment of an adult takes much longer than treatment of a youth (21). Orthodontists treating aviators must select appliances that have a low risk of dislodgment of their brackets, bands, and arch bars. Aviators undergoing orthodontic care should consider not flying for 24 hours after a major orthodontic appliance placement or major adjustment because of the risk that oral discomfort might be distracting to flight operations.

MEDICATIONS

Medications used in general dentistry routinely include antibiotics, analgesics, local anesthetics (with and without vasoconstrictors), nitrous oxide, and intravenous sedation. Dental subspecialists might also use general anesthesia and a much wider variety of systemic medications. For aviators, the impact of these medications on response time, mental processing, coordination, and communication is potentially significant. Dentists should work closely with an aviator's aerospace medicine physician to evaluate the attending risks and plan flight status accordingly (Table 20-2) (22).

TABLE 20-2

Suggested Duty Not Involving Flying (DNIF) Periods

Intervention	*Period*
Local anesthetic	No flight until 8 hr after administration
Endodontic treatment	No flight until 24 hr after root canal is filled
Prescription medication	No flight until 24 hr after discontinuation
Periodontal treatment	No flight until 24 hr after pack is removed
Orthodontic placement/major adjustment	No flight until 24 hr after treatment
General anesthetics	No flight until 72 hr after administration
Intravenous sedation	No flight until 72 hr after administration
Nitrous oxide analgesia	No flight until 72 hr after administration
Osseointegrated implant	No flight until 10 d after phase I and no flight until 10 d after phase 2

CARING FOR ASTRONAUTS

These aviators should undergo a type I examination upon entry to a space flight program. Thereafter, they should have a type II examination and oral prophylaxis every 6 months. At least 2 months before a mission they should have an additional type I examination. All questionable dental conditions should be evaluated and treated, if indicated. International participants in the National Aeronautics and Space Administration (NASA) program should meet the same dental treatment requirements and physical standards as U.S. participants. Civilian space flight participants should also meet these standards.

Astronauts and mission specialists should be trained personally in emergency dental treatment to include oral diagnosis, pain control, local dental anesthesia, dental infection treatment, placement of temporary fillings with *Cavit-G*, recementing prosthetic appliances or crowns with *Dycal*, extraction of teeth, and bleeding control. *Cavit-G* (self-curing zinc oxide composition) and *Dycal* (calcium hydroxide composition) are materials with characteristics that facilitate their use in a space flight environment. Specific dental instruments, materials, and supplies should be included in a "dental kit" aboard shuttles and space stations (Table 20-3). Analgesics and antibiotics for dental treatment should be determined by the dentist in consultation with the aerospace medicine physician and included in the "medical kit." Physicians caring for astronauts, mission specialists, or those in long-course residency training should undergo similar emergency dental treatment training and maintain a dental kit. This way they can provide dental care in remote settings if needed in a dentist's absence.

TABLE 20-3

Sample Dental Kit

Analgesics (in medical kit)	Examination gloves (10)
Anesthesia aspirating dental syringe (2)	Excavator (small, 2)
Anesthesia *Carpule*	Explorer (2)
3% *Mepivacaine HCl* (12)	Extraction elevator no. 301 (1)
4% *articaine HCl* with 1:100,000 *epinephrine* (12)	Extraction forceps no. 150 (1) and no. 151 (1)
Anesthesia syringe needle 27-gauge long (12)	Front surface dental mouth mirror (2)
Antibiotics (in medical kit)	Gauze/sponge (2 × 2 in) (2 packs)
Cavit -G (one jar, or two tubes)	Handheld light (2) with batteries
COGSWELL-A elevator (1)	Instrument disinfection packets (25)
Cotton balls (dental, one pack)	Periodontal scaler (2)
Cotton pliers (2)	Woodson plastic instruments (2)
Cotton rolls (dental, 1 pack)	—
Dycal (2 tubes and applicator)	—

The numbers indicated in parentheses refer to quantity.
HCl, hydrochloride.

CONCLUSION

With this chapter's premier in this text's fourth edition, it follows that aviators, dentists, and aerospace medicine physicians should embrace the opportunity to incorporate oral and dental health into aviators' physical standards to promote their overall wellness from their training on the ground to their aerospace flight.

REFERENCES

1. Harris NO, Garcia-Godoy F, eds. *Primary preventative dentistry*, 6th ed. Upper Saddle River: Pearson Prentice Hall, 2004.
2. *Health insuranc eportability and accountability act of 1996*, 45 C.F.R. §§164.502, 164.506, 164.512 (October 1, 2006).
3. Langland OE, Langlais RP, Preece JW. *Principles of dental imaging*, 2nd ed. Baltimore: Lippincott Williams & Wilkins, 2002.
4. Burket LW, Greenberg MS, Glick M, eds. *Burket's oral medicine: diagnosis and treatment*, 10th ed. Hamilton: BC Decker, 2003.
5. Cawson RA, Binnie WH, Barrett AW, et al. *Oral disease: clinical and pathological correlations*, 3rd ed. Edinburgh: Mosby, 2001.
6. Wilkins EM. *Clinical practice of the dental hygienist*, 9th ed. Philadelphia: Lippincott Williams & Wilkins, 2005.
7. Francischone CE, Vasconelos LW, eds. *Metal-free esthetic restorations: procera concept*, 2nd ed. Sao Paulo: Quintessence, 2003.
8. American Dental Association. *Statement on dental amalgam (updated April 6, 2007)*. Available at: http://www.ada.org/prof/resources/positions/statements/amalgam.asp (last visited July 14, 2007).
9. Summitt JB, Robbins JW, Hilton TJ, et al. eds. *Fundamentals of operative dentistry: a contemporary approach*, 3rd ed. Chicago: Quintessence, 2006.
10. O'Brian WJ. *Dental materials and their selection*, 3rd ed. Chicago: Quintessence, 2002.
11. Okeson JP, Bell WE. *Bell's orofacial pains: the clinical management of orofacial pain*, 6th ed. Chicago: Quientessence, 2005.
12. Walton RE, Torabinejad M. *Principles and practice of endodontics*, 3rd ed. Philadelphia: WB Saunders, 2002.
13. Donoff RB. *Massachusetts general hospital manual of oral and maxillofacial surgery*, 3rd ed. St. Louis: Mosby, 1997.
14. Fonseca RJ. *Oral and maxillofacial surgery*, Vol. 7, 1st ed. Philadelphia: WB Saunders, 2000.
15. Fonseca RJ. *Oral and maxillofacial trauma*, Vol. 2, 3rd ed. Philadelphia: WB Saunders, 2005.
16. Rose LF, Mealey BL, Genco RJ, et al. *Periodontics: medicine, surgery and implants*. St. Louis: Mosby, 2004.
17. Rosenstiel SF, Land MF, Fujimoto J. *Contemporary fixed prosthodontics*, 4th ed. St. Louis: Mosby, 2006.
18. Pheonix RD, Cagna DR, DeFreest CF, et al. *Stewart's clinical removable partial prosthodontics*, 3rd ed. Chicago: Quintessence, 2003.
19. Zarb GA, Bolender CL, Eckert S, et al. *Prosthodontic treatment for endentulous patients: complete dentures and implant-supported prostheses*, 12th ed. St. Louis: Mosby, 2004.
20. Beumer J, Curtis TA, Marunick MT, eds. *Maxillofacial rehabilitation: prosthodontic and surgical considerations.* St. Louis: Medico Dental Media International, 1996.
21. Graber TM, Vanarsdall RL, Vig KWL, eds. *Orthodontics: current principles and techniques*, 4th ed. St Louis: Mosby, 2005.
22. Air Force Instruction 47–101, Department of the Air Force, May 2000.

RECOMMENDED READINGS

Burket LW, Greenberg MS, Glick M, eds. *Burket's oral medicine: diagnosis and treatment*, 10th ed. Hamilton: BC Decker, 2003.

Cawson RA, Binnie WH, Barrett AW, et al. *Oral disease: clinical and pathological correlations*, 3rd ed. Edinburgh: Mosby, 2001.

Okeson JP, Bell WE. *Bell's orofacial pains: the clinical management of orofacial pain*, 6th ed. Chicago: Quientessence, 2005.

Scully C, Cawson RA. *Medical problems in dentistry*. Edinburgh: Elsevier Science, Churchill Livingstone, 2005.

Short MJ, Levin-Goldstein D. *Head, neck and dental anatomy*, 3rd ed. Clifton Park: Thompson/Delmar Learning, 2002.

Thaller SR, Montgomery WW. *Guide to dental problems for physicians and surgeons*. Baltimore: Williams & Wilkins, 1988.

CHAPTER 21

Occupational and Environmental Medical Support to the Aviation Industry

Roy L. DeHart and Steven M. Hetrick

> There are many things that a doctor, on his first visit to a patient, ought to find out either from the patient or from those present. For so runs the oracle of our inspired teacher: ''When you come to a patient's house, you should ask him what sort of pains he has, what caused them, how many days he has been ill, whether the bowels are working and what sort of food he eats.'' So says Hippocrates in his work AFFLICTIONS. I may venture to add one more question: what occupation does he follow?
>
> —*Bernardino Ramazzini 1713 (1)*

The men and women of the aerospace industry, both those on the ground and in the air are exposed to hazards of injury and illness beyond that that is unique to the flying environment. Occupational injuries and exposures are all too common in the workplace and aerospace presents numerous hazards. This chapter provides an opportunity for the student or casual reader to become familiar with the policies and procedures in the United States that have been developed to prevent or manage workplace morbidity and mortality.

Similar policies and procedures are at work to prevent or reduce the harm to the public that is present because of aviation activities. Such risks include transmission of disease by a large fast-flying vector—the aircraft or spacecraft. Arthropods, infectious carriers, and formite transmission have all been transported by aircraft. To some the aircraft becomes a potential hazard to the environment because of the jet or rocket exhaust. This chapter is presented in two major sections: occupational hazards and environmental concerns.

SECTION ONE: OCCUPATIONAL MEDICINE

The American Board of Preventive Medicine defines occupational medicine as that specialty which focuses on the health of workers, including the ability to perform work; the physical, chemical, biological, and social environments of the workplace; and the health outcomes of environmental exposures. Practitioners in this field address the promotion of health in the workplace and the prevention and management of occupational and environmental injury, illness, and disability (2).

In 2005 Paul A. Schulte, PhD a researcher at the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), published an article regarding the national burden of occupational injury and disease on the nation. His research demonstrated that the burden of occupational injury and illness is substantial among America's workforce. In 2002, the Bureau of Labor Statistics (BLS) reported more than

5,500 fatal work injuries, 4.4 million nonfatal injuries, and 294,500 illnesses. In the same year, NIOSH estimated that 3.6 million occupational injuries and illnesses were treated annually in U.S. hospital emergency rooms. His research further addressed a $72.9 billion expense to employers for worker's compensation premiums with a total direct and indirect cost estimated to be in the range of $128 to $155 billion (3).

Each year there is a survey of occupational injury and illness across the United States. This is a federal/state program in which the employer reports are collected from private industry. The survey measures nonfatal injuries and illness and excludes self-employed. farms with fewer than 11 employees, private households, federal government agencies, and the national data system employees in state and local government agencies. The survey provides estimates of the incident rates of the injuries and illnesses based on logs kept by the industry employers during the year. The most current data available (2005) is summarized by industrial sector beginning with the highest incident rate of illness and injury. These data are summarized in Table 21-1. The overall national incident rate was 4.6 cases per 100 equivalent full time workers during 2005.

The census of fatal occupational injuries is also a part of the BLS Occupational Safety and Health statistics program compiled for the United States each calendar year. The data set contains information about each workplace, worker characteristics, equipment being used, and the circumstances of the fatal event.

In his preface to the *Occupational Medicine State of the Art Review* titled The Aviation Industry, Dr. Kendall Green commented that occupational aviation medicine is an amalgam of two specialties of preventive medicine: occupational medicine and aviation medicine (4). He further noted that as a part of preventive medicine, occupational and aviation medicine include the public health and epidemiologic perspectives in addition to the perspectives of "what's best for my patient" commonly seen in clinical medicine.

Aerospace medicine and occupational medicine are part of international coalitions of specialty medical practice. In much of the world, the term *occupational medicine* is better translated in the broader term of occupational health. The World Health Organization (WHO) in 1950 undertook to define "occupational health" as follows:

> Occupational health should aim at the promotion and maintenance of the highest degree of physical, mental, and social well-being of workers in all occupations; the prevention among workers of departures from health caused by their working conditions; the protection of workers in their employment from risks resulting from factors adverse to health; the placing and maintenance of the worker in an occupational environment adapted to his physiological and psychological equipment; and to summarize, the adaptation of work to man and of each man to his job.

In more modern times, the gender bias has been removed and it is well recognized that we have people of both genders actively participating in the workplace.

It was within the context of this definition that the specialty of occupational medicine became formalized. In 1955, a certification program in occupational medicine was established by the American Board of Preventive Medicine. As of 2007, a total of 3,609 physicians have been certified in occupational medicine as compared to 1,423 in aerospace medicine (5).

A key element of both occupational and aerospace medicine is their focus on prevention. Many of the tools used by the profession are those that address illness and injury prevention as well as the clinical topics involved with treatment and management of afflictions, impairment, and disability. Service is provided to a workforce with a demographic characteristic that remains predominantly male in the age-group between 18 and 65. Because of the requirements of employment, most workers are in better health than the general population and enjoy a middle class living standard. In epidemiologic studies that address this population, a term identified as the *healthy worker effect* is important in studying cohorts that are compared with worker populations. Workers in general are in better health with less morbidity and lower mortality when compared to the general population even when gender and age adjusted because they are an employed cohort.

The workplace in the aerospace industry incorporates many of the materials, processes, and operations common to manufacturing in general: airplane repair and maintenance that includes drilling, riveting, screwing, fastening, welding, painting, aluminum layout, template work, subassembly, fuselage fabrication, manipulating large units, replacing of motors, engines, propellers, turbines, wing sections, electronics and avionic equipment, and the inspection of planes, equipment, and machine tool repair. Further, it is often the aviation industry that introduces new machine processes such as the fabrication of titanium structures and

TABLE 21-1

Nonfatal Workplace Injury/Illness Rates by Labor Sector in 2005

Industry Sector	*Rate per 100 Employees*
Transportation	7.0
Construction	6.3
Manufacturing	6.3
Agriculture, forestry	6.1
Leisure and hospitality	6.1
Health and social	5.7
Utilities	4.6
Wholesale and retail	4.1
Mining	3.6
Professional and business	2.4
Information	2.1
Financial	1.7

TABLE 21-2

Work-Related Medical Problems Seen in the Aerospace Workforce

Cuts and lacerations
Dermatitis
Contact
Allergic
Foreign body in eye
Infections
Repetitive trauma
Carpal tunnel syndrome
Tenosynovitis
Raynaud's syndrome
Respiratory tract reaction
Neurosensory hearing loss
Neurotoxic reaction
Central
Peripheral
Strains and sprains
Low back
Cervical
Shoulder

the buildup of metal and carbon fiber composites. Common work-related medical problems occurring in the aerospace industry are enumerated in Table 21-2 (6).

Specialists in aerospace medicine must develop and maintain sufficient orientation and knowledge in the fields of occupational and environmental medicine (OEM) to assist management in obtaining and using the consultation necessary to prevent and solve problems that involve potential toxic hazards arising out of planned operations, products, and waste. In this way, aerospace medicine is better able to encompass the total program of preventive medicine in support of this national industry that is so critical to the economy and national defense.

HISTORY

The relationships of types of work to illness were first addressed by Hippocrates. Centuries later, Ramazzini in his treatise *Disease of Workers* described a constellation of afflictions that befall workers in more than 50 occupational settings (1). As the book was published in the 1700s, it would be surprising if it mentioned anything regarding the aviation industry. Early in the last century, Alice Hamilton, a professor at Harvard's College of Public Health began to visit American industries in the eastern United States documenting her observations and making recommendations to improve the lot of the worker. Her autobiography *Exploring the Dangerous Trades* details some of her experiences with American industry (7).

More recently, Dhenin, a leader in aviation medicine in the United Kingdom observed that aviation medicine is a branch of occupational medicine developed from the need to adapt humans to the hostile environment of the air (8). Although within the United States this observation may be considered controversial by some, it does have its advocates. This recognizes the close relationship between aerospace medicine and occupational medicine, particularly when considering commercial airline and military operations. In 2005 among the major airlines in the United States, only 20% of employees were flight deck personnel and flight attendants, whereas the remaining 80% were classified as ground personnel. Although flight personnel are potentially exposed to many of the hazards unique to flight as described in detail in several chapters of this text, they are also susceptible to occupational illnesses and injuries similar to their ground personnel cohorts.

The U.S. Department of Labor annually publishes labor statistics that include the aviation industry. Table 21-3 lists the type and number of workers in various categories divided roughly into airline operations and aviation manufacturing and maintenance. These figures provide a glimpse of the complexity of the workforce and its distribution in specialties across the industry (9).

To provide a different perspective, the classification of the workforce for a large U.S. international airline hiring approximately 100,000 workers is given in Table 21-4 (10). In recent years, there has been a considerable downsizing of many of the U.S commercial airlines resulting from cost pressure. The head count has become very sensitive to the

TABLE 21-3

Employment in Various Occupational Categories Across the Aviation Industry including Manufacturing, Maintenance, and Airline Operations

Airline operations	
Flight attendants	99,030
Licensed pilots, co-pilots, and flight engineers	26,240
Air traffic control	21,590
Airfield operations	4,500
Ticket agents	97,960
Baggage handlers	9,540
Production workers (other)	2,470
Helpers not otherwise classified	2,090
Aircraft manufacturing and maintenance	
Aerospace engineers	40,860
Aircraft structural systems	20,510
Aircraft mechanics and service technicians	18,070
Operations technicians	5,280
Sheet metal workers	4,070
Electricians	1,230
Aviation technicians	4,720
Computer specialists	2,040
Maintenance personnel	40,930
Cargo	2,350

TABLE 21-4

International Airline Personnel Positions

Position	*Number*
Maintenance and ramp personnel	32,000
Flight attendants	20,000
Agent/planner	13,200
Pilots	11,700
Management	8,536
Reservation representatives	6,500
Staff support	3,200
Total number of employees	95,000

bottom line. For example, in 2003 Delta Air Line's head count was 70,600 employees with a fleet of 833 planes and a cost of 9.36 cents/mi. In 2006, the employee numbers had dropped to 51,000 with a fleet of 625 planes and a cost per seat mile of 6.91 cents (11).

ESTABLISHING AN OCCUPATIONAL AND ENVIRONMENTAL MEDICAL PROGRAM

First and foremost, occupational medicine is a specialty of medicine that is a discipline within preventive medicine. The major goal is to prevent injury and disease and should this not be entirely effective, to prevent death and disability, returning the employee to work as soon as is feasible within the bounds of good health and work capability. This service is far more complex than simply suturing a laceration or performing a preplacement physical examination. The complexities of this practice are complicated by strong regulatory and legislative influences potentially involved with the practice. Physicians have responsibilities that extend beyond the usual clinical situation. A comprehensive program will provide many of the services listed in Table 21-5 (12).

There are many settings and situations in which these services are provided. These range from the office of a family physician to acute care clinics, including multispecialty group practices, hospital-based services, occupational medicine clinics, corporate medical services, and consulting practitioners. The full list of services cited in Table 21-5 will typically be available only in the larger, more comprehensive programs.

The consultant provides a focused service to the aviation industry. Frequently this involves a particular field of expertise, such as toxicology, ergonomics, wellness, or managerial skills, which is available to the industry on a time-limited, but intense, basis. The services of the consultant are usually focused around problem-solving issues and recommendations may include both short-term corrections and long-term solutions.

The types of aviation and space industrial sites where workers are employed are listed in Table 21-6.

TABLE 21-5

Occupational and Environmental Health Services

Disease management
- Emergency response service
- Initial treatment of acute nonoccupational illness
- Periodic health assessments
- Preplacement examinations
- Return-to-work evaluations
- Substances of abuse testing
- Termination examinations
- Treatment of work-related injury or illness

Special assessments
- Biologic monitoring
- Foreign travel
- Functional capacity evaluations
- Hearing conservation
- Prophylactic immunizations
- Radiography (B-reading)
- Respiratory protection clearance
- Spirometry
- Visual screening

Educational services
- Back school
- Cardiopulmonary resuscitation training
- Community education
- First responder training
- Hazard communications: "right to know"
- Vision conservation

Consultation services
- Americans with disabilities act
- Community health
- Disability evaluations
- Employee assistance program
- Environmental hazard evaluation
- Epidemiologic studies
- Expert testimony
- Health physics
- Human engineering (ergonomics)
- Industrial hazard evaluation
- Industrial hygiene
- Medical review officer
- Research protocol development
- Safety engineering
- Toxic hazard information service
- Work-relatedness of disease (causation)

Health promotion activities
- Fitness
- Health screening
- Smoking cessation
- Stress management
- Substance abuse management
- Weight reduction and nutrition

Administrative services
- Evaluation of health-related costs
- Interaction with community physicians
- Management of workers' compensation
- Medical retirement oversight
- Professional supervision of on-site clinics
- Program development

TABLE 21-6

Industrial Sites where Workers are Employed

Aircraft and space vehicle fabrication and repair sites
Aircraft inspection and maintenance centers
Airline operations at airports
Department of Defense aircraft operation centers
Federal Aviation Administrations (FAA) operation and test centers
Military aircraft logistic centers
National Aeronautics and Space Administration (NASA) operational centers
Private and general airports

SCOPE OF PRACTICE

In 2004, the American College of Occupational and Environmental Medicine's (ACOEM) executive board approved a document entitled "Scope of Occupational and Environment Health Programs and Practice." This document provides an excellent summation of the composition and complexities of an occupational medicine practice whether housed in industry, medical centers, and clinic or private offices. It was noted that the role of the occupational physician had expanded in recent years to enhance the productivity of the worker with absent management and increased emphasis on the wellness of the worker. Recently it has been recognized by organizations and regulatory agencies that such trained physicians have expertise in the analysis and development of programs and policies that protect the worker. The doctor may design programs and management health services directed toward defined populations as well as engaging in clinical care of the individual (13). With expansion of the global economy, the American workforce becomes more involved as an integrated member of a global workforce. This requires the physician to understand the needs of the international worker in the local community and ensure that occupational safety and health care in those communities are encouraged toward the best practices. The complexity of the occupational medicine programs in aviation and space requires intellectual and practical skills beyond the clinical arena. Broad-based practices in this industry require professional teamwork and it becomes necessary to enlist and collaborate with the skills and talents of a large number of colleagues in such areas as industrial hygiene, toxicology, occupational health nursing, safety engineering, industrial relations, health physics, engineering, personnel management, biomechanics, law, public policy, and of course health education. Occupational health programs and their practitioners are advancing the field of health and productivity. To accomplish this it is necessary to incorporate a wide spectrum of activities to include occupational health, safety, loss and risk management, absence and disability management, health promotion, disease management, injury prevention, hazard control, and management of health care benefits. A number of these programs are specifically addressed in the following paragraphs.

THE WORK PLACE ENVIRONMENT

Centuries ago, Ramazzini reminded physicians that in order to know the employment circumstances of a worker, one must go to the work site. In aviation manufacturing or flight control operations, the complexities of the work environment can only be understood through direct observation. Recognition, evaluation, and control of hazards posed by chemical, biological, and physical agents, as well as ergonomic stresses and safety risks, require occasional on-site visits. Areas for consideration when providing these services will be discussed further.

Process Descriptions

These are necessary for routine repetitive functions and for special projects that include identification of raw materials, description of processing equipment and conditions (such as temperature and pressure), description of work activities involved, and a description of feedstock, product and intermediaries, by-products, and waste.

Hazard Communications

A chemical inventory is required by the Occupational Safety and Health Administration (OSHA) as detailed in the Hazard Communications Standard. The inventory must be comprehensive and include components of mixtures and identification of chemical constituents of trade name products, and it must remain current. For each chemical in use, information must include chemical and physical properties, as well as toxicity features of animal and human exposure at levels thought to be safe for occasional and daily exposure. Material safety data sheets (MSDS) are required for each chemical that is used at the industrial site as directed by the Hazard Communications (right to know) regulation. In addition to toxicologic information, there is additional information and other precautions to be observed in handling, storing, and emergency control measures in cases of spills. Names and phone numbers of individuals to contact for additional information or assistance are listed. From a medical information point of view, the MSDS provides instructions to emergency responders on how to initially manage a worker who has been exposed at a high enough level to cause adverse symptoms.

Listing of Employees

A list of each employee with consecutive job titles and work assignments as well as some method for identifying potential chemical exposures should be available. Personnel or environmental monitoring of levels of chemicals or physical agents must be recorded and indicate sampling strategies, procedures, and dates. Ideally, there should be a cross-indexing of workers, job titles, work areas, and projects to allow for comprehensive review of potential past exposures. This is frequently needed for comprehensive medical surveillance of employee exposure. It is not uncommon to find similar listing but only for the current job held by the employee. Because of the issue of long intervals between exposure and appearance of adverse health effects such as cancer the entire work history combined with exposure history is important.

Reports of Occupational Injury and Illness

Such reports are frequently listed in the OSHA 300 Log, a separate listing of injuries and illnesses that occur in the workplace, and identify the injured worker, the circumstances of the injury, and the degree of medical intervention. This record is helpful in identifying workplace problems so that solutions can be identified and implemented. The log is used to notify federal agencies of the occurrence of accidents and injuries. Such data may be used to establish periodic inspections of the workplace by such state or federal entities.

Control Measures

For controls to be effective requires interdisciplinary cooperation between medicine, engineering, industrial hygiene, and management. The implementation of control technologies is most effective and economical when they become a part of the original design and installation. Removing the hazard through control procedures is by far the best preventive medicine action. When solvents or other feedstocks are considered, a product toxicologic review of the material before its procurement may lead to a far safer item than trying to institute control measures after the fact.

EMPLOYEE TREATMENT, EVALUATION, AND EDUCATION

Employee treatment, evaluation, and education are occupational medicine services that at one time were commonly provided by the employer on site, but have become a part of the ‘‘sizing’’ of American industry and have frequently been outsourced. These types of services, whether in-house or not, have both medical and nonmedical components. Providing treatment for occupational injury or illness is the obligation of the employer. Such treatment should be handled either by on-site medical personnel or be referred. Complicating health care management is the insurance system that exists in all states and federal agencies known as *Worker Compensation* to be discussed further.

Work Placement

Work placement may depend on the nature and extent of limitations of function caused by medical conditions. Evaluation of such limitations when preplacement medical examinations are performed may influence the proper placement of potential employees. The occupational medicine physician needs to become familiar with the Americans with Disability Act (ADA). This federal program was put in place to ensure that an employee is not discriminated against unfairly when seeking a job. Since its implementation in 1992, it has been more precisely defined through the courts.

Medical Surveillance

The program of medical surveillance provides information on ‘‘target organs’’ that may be adversely affected by a particular hazard or multitude of unknown agents. Surveillance programs help to assess the adequacy of protective measures. Medical surveillance includes the development of a baseline health inventory followed by periodic reevaluation. Medical surveillance is not intended to be the sole method for control of exposures to such chemicals. Its intention is to be used as a check on control policies and procedures within the workplace.

Epidemiological Surveillance

This type of surveillance can help detect possible work-related adverse health effects. Prudence dictates epidemiologic evaluation of health indicators for those worker populations with potential exposures to possible health hazards.

Education

Employee and supervisor education that addresses workplace health factors is vital in preventing illness and injury. There are also significant ethical, legal, regulatory, and employee relations reasons for programs to educate the workforce.

Training

Employee and supervisor training in proper work practices and in the use of personal protective equipment may be required or appropriate. Special training is frequently necessary for employees to meet the emergency, first aid, and cardiopulmonary resuscitation needs of the facility. In certain situations, the OSHA Hazard Communication Standard requires employee training and education.

Employee Assistance Programs

The Employee Assistance Programs (EAP) provides vitally important services for troubled employees and their families. The comprehensive approach, which may include counseling on marital, financial, and interpersonal issues, is generally more effective than simply limiting such intervention to the traditional alcohol and drug abuse problem. Opportunities for self-referral and confidentiality are important program considerations.

Health Promotion

Wellness programs dealing with nonoccupational health situations such as smoking cessation, nutrition, fitness, and other lifestyle issues are increasingly important, and their value to both the worker and industry are now well documented (14,15).

PROGRAM ADMINISTRATION

Close interaction with company management and employee representatives (union) is essential to provide a properly tailored, workable program of occupational health services.

Policies and procedures are management tools that are appropriate to the work site and may be developed by the OEM physician with the concurrence and endorsement of the management and the union.

General Liability

General liability considerations are important to prevent claims of willful negligence against the practitioner or the company. Meticulous attention to ethics, medical management, communications, and record keeping are the main stays of defense. Malpractice liability applies to the private practitioner and the corporate physician alike, although the circumstances and degree of liability may vary.

Information Management

This tool provides the basic information necessary for a successful program. Federal requirements concerning retention of medical data must be understood and observed. For example, radiographs obtained as part of an asbestos surveillance program must be retained and available for 30 years past the termination of the employee. Communications and coordination are required with workers, technical experts, supervisors, management, and other appropriate people.

REGULATORY AND ADVISORY AGENCIES

As in many fields of endeavor in which humans engage in an industrial society there are regulations, rules, laws, and policies. In the field of OEM, there are a number of entities at both state and federal level that provide advice, recommendations, training, and research as well as serve as regulatory agencies with police power. An efficient and effective occupational health program must comply with regulations and seek out and use educational and advisory information. A number of these agencies, administrations, and institutes are described in subsequent text.

Occupational Safety and Health Administration

The passage of the Occupational Safety and Health Act in 1971 created the OSHA and the NIOSH. The primary regulatory agency for occupational safety and health is OSHA. Its standards have the weight of law throughout the United States and its compliance officers can inspect the workplace at anytime to determine the status of health and safety. If a serious safety violation is found that could result in immediate harm to workers, the establishment can be closed. The agency can use the power of a court order citation or fine to enforce compliance. States may elect to have their own programs and half have done so. The state program must, as a minimum, meet all the regulations and other requirements established by federal OSHA. This is an agency of the Department of Labor and as such develops regulations, which are announced through the Federal Register.

One of the early standards established permissible exposure limits (PELs) for hundreds of chemicals. To accelerate the standards-setting process OSHA was permitted to adopt as a consensus standard the threshold limit values (TLVs) established by the American Conference of Governmental Industrial Hygienists (ACGIH). In an agreement signed on August 7, 2000 OSHA and the Federal Aviation Administration (FAA) pledged to work together to improve the working conditions of flight attendants while aircraft are in operation. As a first step the two agencies formed teams to review OSHA standards on record keeping, blood-borne pathogens, noise, sanitation, hazard communication, and access to employee exposure and medical records. Previously OSHA enforced standards for maintenance and ground support personnel in the airline industry while the FAA provided assessment of hazards related to flight deck personnel (16).

Currently both the OSHA PELs and the ACGIH TLVs are operative. Each year the ACGIH publishes TLVs for chemical substances and physical agents as well as biological exposure indices. This small handbook, which readily fits into a briefcase, makes readily accessible many of the hazardous exposure levels that should be avoided in the workplace. The nature of the standards-setting process makes the modification of current or the introduction of new PELs extremely cumbersome. The altering or adding new TLVs, although discussed and at times controversial, is far more expeditious and therefore may represent the more current scientific thought. To add further complication to these values is the NIOSH recommended exposure values (REVs). These levels are believed to be low enough that they would constitute levels with no adverse health effects for any worker.

National Institute for Occupational Safety and Health

NIOSH is an arm of the Department of Health and Human Services and is housed at the CDC. Like OSHA, NIOSH has the authority to conduct inspections and to question employees and employers and even to include the use of warrants to acquire information on workplace conditions. However, it is not a regulatory agency and cannot levy penalties and this fact enhances its ability to serve as a consultant. Further, it serves the occupational and environmental health community as an educational resource providing not only material but also financial support for educational programs such as residencies in occupational medicine. Funding support is also provided to research projects in the field of OEM.

Environmental Protection Agency

The Environmental Protection Agency (EPA) was created to enforce the Toxic Substance Control Act (TSCA) as well as other regulatory functions. It is responsible for regulating the quality of water and air and addresses numerous environmental problems such as hazardous waste sites. When it comes to the workplace, EPA must take a backseat to OSHA until hazardous waste, air or water pollution, or other hazardous substances leave the plant site. The EPA works with other agencies in serving as an educational and training source as well as collecting and disseminating information on hazardous materials. Like OSHA, EPA is a regulatory agency and has all the powers necessary for enforcement.

Assisting EPA in the same way that NIOSH provides recommendations for regulatory activity to OSHA is the Agency for Toxic Substances Control Registry (ATSDR). Two publications which are the responsibility of ATSDR that are of value to physicians are the "Toxic Profile" series on individual hazardous chemicals and the "Case Studies in Environmental Medicine" series using case studies as a method to educate physicians.

WORKPLACE HAZARDS

The aviation industry has the potential of exposing the workforce to numerous hazards that may result in adverse health effects. To assist in the systematic review of the major hazards of concern, they are categorized as chemical, physical, biological, and ergonomic.

Chemical Hazards

In many respects, to define a substance as a toxic chemical is redundant. Essentially all chemicals are toxic, given a specific route of exposure or an excessive dose. A gallon of water becomes toxic when inhaled; oxygen can induce convulsions when breathed under hyperbaric conditions; 500 g of table salt taken orally at one setting will have serious adverse effects on metabolism. The topic of toxicology is complex and still evolving.

Chemical hazards are harmful substances that may be encountered anywhere in the workplace and have been classified in various ways. Such a classification would include the physical characteristics such as dust, fumes, mist, vapors, gases, and liquids. Another classification can address the chemical class of the hazard and would include acids, bases, solvents, metals, petroleum products, and geologic derivatives such as silica, asbestos, coal, and petroleum. The toxic manifestation of the chemical is related to the steps it undergoes in its interaction with the body. These include uptake, distribution, metabolism, storage, and excretion. To fully understand the toxic manifestations of the chemical, one is required to study these steps in order to understand the adverse effects produced by these interactions. Further information is available in Chapter 9.

Threshold Limit Values

The intent of TLVs set by consensus within the ACGIHs TLV committee is to provide reliable benchmarks to aid plant engineers, both in designing new facilities and in renovating old ones, so that the possibility of toxicity occurring in the workforce is minimized (17). In this way, other protective measures such as personal protection, limiting exposure time, and special-purpose occupational medical examinations and tests could either be minimized or better still, documented as being unnecessary. The basic premise involved in industrial hygiene controls below a permissible (safe) exposure level is that repeated exposures over an 8-hour day, 5 days a week for a working lifetime of approximately 40 years could be allowed for most unprotected employees without harm. Although a few susceptible individuals in the workforce might develop evidence of harm, these persons would be detected by close occupational medical surveillance and removed or protected from further exposure before sustaining irreversible impairment or disability. The individuals who are sensitive or allergic to the chemical in question fall outside the proposed permissible limit, as there may be no safe limit.

Unfortunately, the facts that would help place matters of environmental and occupational health into proper perspective are not being communicated adequately to many of our citizens. As a result, a climate exists now in which the adverse effects on productivity and the economy are disregarded while sensationalistic, science fiction–type coverage in the media of environmentally induced illness claims are encouraged and even rewarded. The concept of absolute assurance appears to be the rule that it is reasonable to expect absolutely no risk to the individual, the community, or to the environment from activities of commerce. This tendency toward zero-exposure levels for many chemicals is cost prohibitive and may be without scientific merit. The attitude of some that industries must prove the nonevent, that is that a chemical is absolutely safe, violates the established and well-recognized limitations of epidemiology. There needs to be greater assurance that appropriate instruction in environmental and occupational health occurs at all levels within the biomedical community. For more information on toxic chemicals and toxicology generally, the reader is referred to Chapter 9.

Biological Monitoring

Where environmental surveys cannot document adequacy of hazard control below a limiting federal standard (usually half the PEL), special purpose occupational medical examinations and biological monitoring may be required, even if proper protection is worn. Biological monitoring, for example, is required when there is asbestos or benzene exposure beyond the regulated levels. Conversely, where environmental data confirm the adequacy of hazard containment, only a preplacement baseline value may need to be established. To accomplish biological monitoring on a routine basis in the absence of potential hazardous exposures is unjustified due to the administrative burden, the cost of the tests, and the deviation of the worker away from his or her task.

Physical Hazards

Physical hazards are defined by Wald as hazards that result from energy and matter, and the relationship between the two (18). Operationally, these hazards as they exist in the workplace can be organized into worker–material interfaces, the physical environment, and energy and electromagnetic radiation. Each of these is present in the aviation industry. Physical agents are formless and essentially weightless, but

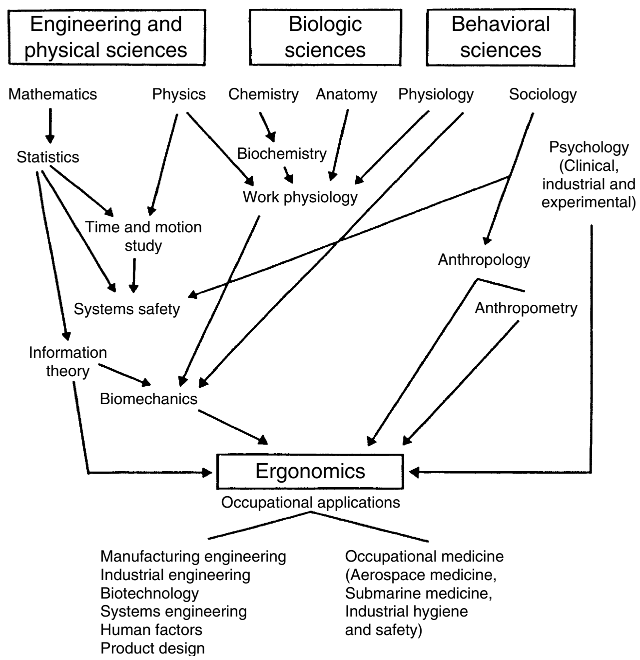


FIGURE 21-1 Disciplines in ergonomics. (From Zenz C, Dickerson OB, Horvath EP, eds. *Occupational medicine*, 3rd ed. St. Louis: Mosby-Yearbook, 1994.)

may produce hazards to exposed workers by the transfer of energy of various types, resulting in rather specific bioeffects when permissible occupational standards are exceeded. Among the most important potentially harmful physical agents where there is a transfer of energy are (a) oscillatory motions, including noise and vibration; (b) extreme occupational temperature variations in the ambient environment; and (c) ionizing and nonionizing electromagnetic radiation. Figure 21-1 introduces other forms of physical hazards on the job that are typically defined as ergonomic or biomechanical but also have important consequences to worker health, safety, and productivity (19). Many of these hazards are discussed in detail in other chapters within this text (see Chapters 4, 5, and 7).

Electromagnetic Radiation Hazards

The electromagnetic radiation hazards (EMRs) spectrum encompasses an unbroken series of ethereal waves, moving with the velocity of light that vary widely in wavelength from cosmic rays as short as 4×10^{-12} cm to hertzian waves (used in radio and power transmission), which extend several miles in length. For purposes of hazard evaluation and control, EMR falls into two distinct categories based on the ability to dissociate a substance in solution into its constituents or ions. These categories are universally identified as ionizing radiation (IR) and nonionizing radiation (NIR). For further details on these hazards in the aerospace environment, the reader is referred to Chapter 8.

Biological Hazards

Biological hazards may cause illness as a consequence of their infectious or toxic properties or because they may act as antigens and produce an adverse immune response. Such hazards are uncommon in airframe manufacturing, but of major concern in flight line operations. A noted exception in manufacturing is biological agent contamination of machine cutting fluids that are used to disperse heat and assist in removing metal cuttings.

In 1960, the first Report and Guide to Hygiene and Sanitation in Aviation was published. This addressed many of the flight line operational issues related to biological hazards. Disposal of passenger-generated waste presents a potential infection hazard to ground personnel. Animal transport by air introduces the possibility of spread of zoonoses to airline and ground personnel. The aircraft as a vector for disease transmission is addressed in Section Two of this chapter.

Ergonomic Hazards

Ergonomics has been defined by Chaffin as the science of fitting the job to the worker (20). In both flight line operations and aircraft manufacturing, this interaction of workers with machines focuses on the one hand with compatibility of the worker's capabilities and limitations, and the job requirements and machine interface on the other. Ergonomic design is well appreciated in the cockpit, but may receive little consideration in engineering the job of a millwright in a cutting machine operation or the biomechanics of baggage handling for ground personnel. Ergonomic hazards are defined as physical stressors and environmental conditions that pose a potential risk of injury or illness to a worker. These physical stressors are described as repetition, force, posture, and vibration. To these stressors must be added the issues of poor job design; inadequate workstation layout; and negative work organizational factors such as work rates, shift work, work-rest cycles, and managerial insensitivity.

Human-related error counts for approximately 70% of all transportation accidents including aviation. Fatigue is a significant factor that contributes to human error in the industry. The Air Transport Association (ATA) has developed an alertness management guide to assist those in industry in managing, preventing, and providing countermeasures to operational fatigue. In December 2000, the ATA established an Alertness Management Initiative Scientific Advisory Board to address alertness in flight operations (21).

Disregarding ergonomic factors can lead to work related injury and disability. Assembly-line work that requires a repetitive cycle of less than 30 seconds is associated with upper extremity musculoskeletal injury. The application of poor body mechanics to lifting, pulling, or pushing is a major contributor to low back pain and disability. The significant increase in carpal tunnel syndrome over the last 20 years has been attributed in part to repetitive injury and biomechanical strain. In 1985, NIOSH released its Proposed National Strategy for the prevention of work-related musculoskeletal injury (22). This documented the need to control work-related low back injuries as a national goal. One of the resulting strategies was the development of new lifting guidelines. This effort led to the development of the revised 1961 Lifting Equation for Material Handling (23). In 2000, OSHA promulgated a new standard for ergonomics that had been in preparation for nearly a decade. Within months of its publication and before its implementation, it was rescinded by Congress. To date (2007), a new ergonomics standard has not been forthcoming.

Currently OSHA has a four-prong approach approved to address ergonomic issues as follows:

1. Guidelines that are developed for specific industries.
2. Inspections for ergonomic hazards with citations issued under the general duty clause.
3. Outreach and assistance to employers for program development.
4. Formation of a national advisory board

To determine ergonomic risk, it is helpful to perform a job analysis that evaluates job requirements and psychophysiologic variables, as well as environmental factors. This is the hallmark of prevention: anticipating risks, validating the degree of risk, and then modifying or reducing the risk to avoid biomechanical injury.

OCCUPATIONAL MEDICINE CASE STUDIES FROM THE AEROSPACE INDUSTRY

Since the period of World War II in the mid-20th century, numerous occupational and environmental health studies were conducted in the aerospace industry. A number of these studies are reported to provide the reader with examples of occupational hazards at play in this industry.

Jet Fuel

Jet fuel is currently used by the U.S. Air Force in most of its inventory of aircraft and in some of the military vehicles and auxiliary ground equipment found at air force bases. Consequently, all operational personnel encounter some level of exposure to jet fuel whether through direct occupational exposure or through incidental contact. Jet propellant-4 (JP-4) was first specified in 1951 as a 50–50 kerosene–gasoline blend. It was the primary U.S. Air Force fuel used between 1951 and 1995. It exists as a mixture of aliphatic and aromatic hydrocarbons and contains a number of additional additives. It is a flammable, transparent fluid with a clear or straw color and a strong kerosene-like smell. More recently, JP-8 has replaced the older fuel type. The transition was complete in 1996 and was due to the need for a less flammable, less hazardous fuel. Both formulations are projected to remain in the inventory until 2025. A commercial aviation version is identified as JET-A. Although JP-8 contains less benzene and less n-hexane, it does have a stronger kerosene smell and an oily feel to touch.

Recently developed technology was used to collect samples of exhaled breath from various groups of military personnel. These samples were analyzed in the laboratory for the presence of constituents of the jet fuel. Through the breath analyzing techniques, investigators were able to quantify human exposure levels and included inhalation, dermal, and ingestion exposures. This jet fuel is similar to commercial international jet fuel A-1. The results demonstrated that exposure occurred with all subjects ranging from slight elevations as compared to a control cohort to more than 100 times the control value with those actively exposed in the workplace. Long-term health effects are yet to be assessed (24).

Mortality Study Among Aircraft Manufacturing Workers

In 1999, a report detailing mortality among aircraft manufacturing workers was published. The purpose of the study was to evaluate the risk of cancer and other diseases among workers engaged in aircraft manufacturing that were potentially exposed to compounds containing chromate, trichloroethylene (TCE), perchloroethylene, and mixed solvents. The investigation was a retrospective, cohort, mortality study employing standardized mortality ratios (SMRs) between workers and the general population. The study cohort comprised approximately 78,000 workers who had accrued 1.9 million person years of follow-up. The results of this large study following workers for more than three decades provided no clear evidence that occupational exposures at the aircraft manufacturing factory under study resulted in increases in the risk of death from cancer or other diseases. The overall mortality experience was low with all causes of death attaining an SMR of 0.83 and a cancer mortality with an SMR of 0.90 (25).

Aircraft Workers Exposed to Trichloroethylene and Associated End-Stage Renal Disease

The U.S. Renal Data System (USRDS) had reported that in 2001 there were 406,081 cases of end-stage renal disease (ESRD) prevalent in the United States and more than 96,000 incident cases. Patients with ESRD have chronic renal failure that has advanced to the point that they require either dialysis or renal transplant to survive.

Identification of potential occupational causes of renal failure is difficult because of the complex multifactorial etiology of the disease, time lag between exposure and disease, and the nonspecific nature of the renal histopathology once it advances to the end stage.

Hydrocarbon TCE is a major industrial solvent that has been used in numerous occupational settings, particularly as a metal degreaser.

In 2006, Radican et al. (26) published the results of a retrospective, cohort study that suggested exposure to hydrocarbons might increase the risk of ESRD. The study compared the risk in exposed versus unexposed workers at Hill Air Force Base for the period 1973 through 2000. However, exposures were not mutually exclusive and the investigation was limited in its ability to draw strong conclusions about risks associated with individual hydrocarbons.

The study used data from three sources: a database of former employees at the airbase, mortality data taken from the National Data Index, and ESRD incidence data from the USRDS database. The Hill cohort comprised all civilian employees at the aircraft maintenance facility for at least 1 year between January 1, 1952 and December 31, 1956. The cohort included 14,155 workers of both genders of which approximately one half had been exposed to TCE.

As an estimate of intensity of exposure, a cumulative exposure score was generated for TCE that considered individual subjects based on frequency, duration, calendar period of use, and years of exposure.

For the time period 1973 through 2000, there was an approximate twofold increased risk of ESRD among workers exposed to TCE, trichloroethane, and JP4 gasoline compared with unexposed subjects all significant at less than 0.05 (26).

Mental Health Outcomes in F111 Maintenance Workers Replacing Fuel Tank Seals

In 1973, the Australian Air Force obtained the F111 aircraft. In subsequent years, there was a need to replace fuel sealant material as the F111 does not have a dedicated fuel bladder but instead the fuel occupies the empty spaces between other structures and the shell of the aircraft becomes a giant integrated fuel tank. This design clearly required some form of effective sealant to ensure that surfaces and internal structures did not pose fuel leak problems.

In Australia, four fuel tank repair programs ran for over two decades from 1975 through 1999. Each involved different processes and used a range of approximately 60 hazardous substances, mainly organic solvents. In conducting reseal operations, workers would frequently spend extended periods, sometimes up to 5 hours inside the fuel tanks in conditions that were cramped, inadequately ventilated, hot, and with poor communication capacity. Such work was suspended in January 2000 as an initial investigation revealed that the current spray seal process generated symptoms consistent with solvent exposure in the workers. Health effects were assessed in a sample of 105 individuals. A total of 47% of these reported some neurologic/psychological symptoms. These included anxiety/stress, claustrophobia, depression, indecisiveness, irritability, mood swings, paranoia, loss and/or lapses of memory, psychological problems, exhaustion, headache, and head pain.

This led to a formal retrospective cohort study to evaluate the possible association between the sealant operation and adverse health status. The study involved mailed questionnaires in addition to a series of clinic assessments with consenting participants. In addition to workers exposed to the sealant operation, two other comparison groups not involved in this kind of exposure were used. Of a total of 872 exposed 592 or 68% consented to participate. The nonexposed cohort consisted of 980 personnel.

The results of this epidemiologic study found a consistent and robust association between participation in sealant operational activity and poorer mental health, particularly depression and anxiety, as measured by standardized modules, physician diagnosis, and medication use (27).

Airborne Polycyclic Aromatic Hydrocarbons at an Airport

Polycyclic aromatic hydrocarbons (PAHs) are a group of ubiquitous organic substances made up of hundreds of compounds that include mutagens and carcinogens. Populations may be exposed to PAHs by inhalation of environmental air polluted by the emissions of petroleum-fueled engines or natural sources. Although data on occupational exposure to PAHs are available for many work categories, the literature provided no information concerning occupational exposure to airport staff. Exposure to these workers may be caused by emissions from motor vehicles in use around the airport or from aircraft exhausts.

The aim of this study, conducted at an Italian airport, was to measure concentrations of 25 congeners, including biphenyl, by means of a sampling method able to separate vapor and particle-bound fractions of PAHs. Sampling was performed in January and February 2005 at fixed points around the airport that included the baggage area where transport vehicles unload to conveyor belts, a runway with heavy plane and motor vehicular traffic, and the departure lounge. Twelve 24-hour air samples were taken. Although the PAH levels were generally low, higher levels of naphthalene and biphenyl were found. Of more concern was the increase found in levels of benzofluoranthane and benzopyrene (28).

Advanced Composites

Recognizing that military aircraft contain advanced composite materials as well as fiberglass, a study was conducted at McClellan Air Force Base to determine the most effective engineering control for dust and fibers generated during advanced composite and fiberglass repair operations. Composite materials that were tested consisted of reinforced fiber and a resin. The fibers within composites are the load-bearing elements while resin molecules fill the voids and transfer the stress from fiber to fiber. The field studies demonstrated that a movable exhaust hood with flexible ducting provided the best control of contaminants generated during repair operations (29).

WORKERS' COMPENSATION

At the end of the 1800s in Great Britain and beginning in the first decade of the 20th century in the United States, a social concern arose for the plight of the worker injured or made sick because of his employment. When a man could no longer, for whatever reason, earn a living he might become destitute and his family wards of society. State by state legislation was introduced that provided protection to the worker and his family should the cause of his impairment be his work. Industry was forced to provide for this worker and workers' compensation became a mature insurance plan with three components. The first component was to assure that the injured worker received prompt and proper medical care with no personal expense. The second component provided some protection for short-term wage loss resulting from the inability to work. The third component provided financial relief with monetary reimbursement should the worker sustain a permanent impairment due to the loss of or the loss of use of a body part or a sensory function such as vision.

In the United States currently there are separate workers' compensation systems in each of the 50 states and numerous systems within the federal government. For example, within the military services, the member is provided medical care and the service pay continues. If retired for medical reasons related to service, the member receives ongoing long-term care from the Veterans' Administration and may qualify for a medical pension. If a civilian works for a government entity such as National Aeronautics and Space Administration (NASA) or the Department of Defense, the Department of Labor manages the workers' compensation program. Because of the wide variety of workers' compensation systems, a common concern for occupational medicine services provided to the airline industry, whether it be in manufacturing or airline operations, is the management of the workers' compensation system. For the airlines, as a transportation industry, operating in multiple states and across international borders, the management of various components of workers' compensation is frequently involved, complex, and complicated by an enormous governmental bureaucratic system. Airframe manufacturers may have similar concerns as they frequently have multistate operations. As workers' compensation is a no-fault insurance program with "first dollar pay" for medical expenses it represents a major cost to the employer. In both state and federal systems, the workers only legal remedy for most job-related accidents or illnesses is through this system. There is reasonable assurance that the worker will receive medical care at no cost, will receive partial reimbursement for lost wages after a minimum qualifying period, and should there be permanent impairment or disability resulting from the job-related injury or illness will receive proportional compensation. At the same time, the employer is spared the inconvenience and expense of lawsuits for injuries occurring on the plant property. Coverage is for all employees including flight crew and ground personnel. To reduce the bureaucratic morass with each state having an independent system, a solution achieved by several airlines through labor negotiations involves identifying a single state that will always have jurisdiction regardless of the geographic location of the incident, or the party may be able to file at the home base location regardless of where in the world the injury occurred.

The management and administration of workers' compensation should assure fairness, encourage appropriate medical management, early recovery, and minimize financial loss to both the worker and the employer. An alternative duty (light duty) policy is a critical element for success in effectively returning the worker to the workplace. Laws and procedures that vary significantly can be major sources of frustration to all.

In 1996 the Public Law 104-191: Health Insurance Portability and Acceptability Act (HIPAA) was passed. This law gave patients the right to protect their health information. This applied to health care providers, institutions, and insurance providers. In most jurisdictions, if the patient (worker) files for workers' compensation insurance the privacy protection provided by HIPAA may be waived. If providing care or managing such programs, the OEM provider must be knowledgeable of the intricacies and application of this law.

THE AMERICAN COLLEGE OF OCCUPATIONAL AND ENVIRONMENTAL MEDICINE

The college was originally founded in 1916 and is the nation's largest medical society dedicated to the promotion of health of workers through preventive medicine, clinical care, research, and education. The association comprises 31 component societies in the United States and Canada whose members hold scientific seminars and meetings. The college sponsors the annual American Occupational Health Conference in the spring and is the nation's largest conference of its kind. In the fall, there is the State-of-the-Art Conference that meets in a smaller venue and conducts a more rigorous update of the science of occupational and environmental medicine. ACOEM publishes the peer-reviewed Journal of Occupational and Environmental Medicine as well as a number of other communication pieces. These activities promote the mission of the college that includes educating health professionals and the public, stimulating research, enhancing the quality of practice, guiding public policy, and advancing the specialty. As an international society, ACOEM is the world's largest such professional organization with more than 5,000 occupational medicine physicians. In 1998, the ACOEM board of directors identified a spectrum of competencies that formed the basis of the practice of the specialty. Although this list does not specifically define a "core set" but rather defines a "menu" that is more reflective of the wide variety of interests and activities of physicians practicing occupational and environmental medicine. This menu builds upon a foundation of general clinical competencies to which are added education, experience, and interest. Another recent development made by the college is the development of the Occupational Medicine Practice Guidelines that is now in its second edition. The guidelines provide high-quality, evidence-based recommendations for patient management. Another document that was developed by the college's board and has undergone several revisions is its Code of Ethical Conduct. A discussion of ethics concludes this section.

ETHICS

For whom does the occupational medicine physician work? That is the question that each physician must not only ask but also answer when entering the field of occupational medicine. It must be realized that the simple answer, "the patient," may not always be appropriate. For example, the recommendation to halt a manufacturing process because it may have high risk to a worker but may cost the job raises the question: does that serve the worker? Is the job applicant upon whom you perform a preplacement examination "a patient?" Is making a recommendation regarding fitness-to-work best serving "the patient" when you have no idea what the duties of the job entail? Do you have a professional, ethical, or moral obligation to the employer who may be paying your salary or the bill?

Ethical issues frequently arise in occupational medicine practice because of competing interests, economic issues, regulatory requirements, and organizational power structures.

In defining ethics, Rest describes what it is not before indicating what it is (30). Ethics is neither law nor social custom; it is not personal preference or consensus. Rather she holds that ethics is a guide for action that is consistent to held values, principles, or rules that are able to withstand close moral scrutiny.

In 1993, the ACOEM, revised its Code of Ethical Conduct and has subsequently reviewed and confirmed the code on several occasions (31). These standards are intended to guide occupational medicine physicians in their relationship with the individuals they serve: employers and workers' representatives, colleagues in the health profession, the public, and all levels of government including the judiciary.

Physicians should:

1. Accord the highest priority to the health and safety of individuals in both the workplace and the environment
2. Practice on a scientific basis with integrity and strive to acquire and maintain adequate knowledge and expertise upon which to render professional service
3. Relate honestly and ethically in all professional relationships
4. Strive to expand and disseminate medical knowledge and participate in ethical research efforts as appropriate
5. Keep confidential all individual medical information, releasing such information only when required by law or overriding public health considerations, or to other physicians according to accepted medical practice, or to others at the request of the individual
6. Recognize that employers may be entitled to counsel about an individual's medical work fitness, but not to diagnoses or specific details, except in compliance with laws and regulations
7. Communicate to individuals and/or groups any significant observations and recommendations concerning their health or safety
8. Recognize those medical impairments in oneself and others, including chemical dependency and abusive personal practices, which interfere with one's ability to follow the principles mentioned earlier, and take appropriate measures

Professionals of good conscience may differ in the interpretation of such guidelines. The long-term focus should not be on the differences but rather on the continuing dialogue that helps to craft refined definitions that meet the expectations of a widening circle of professional colleagues, workers, and employers.

SECTION TWO: ENVIRONMENTAL AND PUBLIC HEALTH ASPECTS OF AEROSPACE MEDICINE

Thank God man cannot fly, and lay waste the sky as well as the earth.

—*Henry David Thoreau*

ENVIRONMENTAL MEDICINE

Aircraft operate within an atmospheric environment that can potentially pose a host of hazards to crew and passengers. The aircraft hull creates a closed microenvironment that is susceptible to concentrating physical, chemical, or biological hazards. Over the last 20 years, there has been growing awareness of the potential effects aviation may be having on the atmospheric environment. Additionally, the explosive growth in the aviation industry to commonplace occurrence has resulted in significant implications for public health, especially in the realm of communicable disease transmission. The high-density occupancies and proximity between passengers innate to commercial aircraft have implications for contact, droplet, airborne, and vector borne disease modes of transmission.

The specialty of environmental medicine focuses on the causes of disease and injury in an environmental context and explores the interactions between environment and human health. As the specialty relates to aviation, this section will discuss environmental issues related to the aircraft cabin, the impacts of aviation on public health, and finally, the impact of aviation on the surrounding community and global environment.

AIRCRAFT CABIN ENVIRONMENT

As was made apparent in earlier chapters of the text, aerospace vehicles operate in environments quite hostile to their human occupants. Faced with a cold, hypobaric, hypoxic, and potentially ozone-contaminated flight corridor, aircraft are challenged with providing a microenvironment suitable for the health and comfort of crew and passengers. Hazards, either brought in from outside the aircraft or generated from within the cabin, have the potential to concentrate to levels detrimental to crew and passenger health. Passengers and crew themselves can be the source of cabin contaminants in the form of bioeffluents, viruses, bacteria, fungal spores, and various allergens.

As air travel has burgeoned into a commonplace means of mass transportation utilized by 1.5 billion people, there has been much written in the trade, lay, and scientific literature on aircraft cabin comfort and air quality (32). Akin to two people in a room disagreeing over it being too warm or too cool, the perception of comfort in an aircraft can be as varied as the number of people onboard. Passengers and cabin crew frequently complain that the air on planes is unpleasant and may be unhealthy (33). Trade and lay publications tend to be less than rigorous in scientifically linking complaints of crew or passenger discomfort to cabin air quality.

The scientific literature reports headache, fatigue, and respiratory symptoms among the more common complaints, especially on long duration flights, in which cabin air quality is questioned. A difficulty in interpreting many of these studies is the general lack of health effects data for passengers and crew collected in conjunction with clear exposure information. Therefore, it is difficult to establish a causal relationship between poor cabin air quality and adverse health effects (34). It is also important to note that the literature centers upon cabin air quality under routine operations. Owing to mechanical failure or adverse flight incident, smoke, engine oil, hydraulic fluid, or de-icing solution could be introduced into the cabin, creating a frankly toxic environment for occupants. Two environmental factors that may contribute to complaints about air quality are low relative humidity and pesticide use (Table 21-7).

Nagda and Koontz reviewed 21 studies of reported flight attendant health and comfort in airliner cabins published from 1980 to 2000 (35). These studies employed in-flight surveys or general flight experience surveys. In addition, some research included objective measurements of test subjects, such as pulmonary function tests or pulse oximetry. Recognizing shortcomings such as small sample sizes, poor response rates, and response bias, this body of studies illustrates the fact that flight attendants perceive that they develop a host of symptoms related to the airline cabin environment. Frequently reported symptoms include dryness, fatigue, bloating, headache, and earache. It is important to bear in mind that many of the "air quality" studies occurred before the smoking ban.

TABLE 21-7

Factors Involved in Cabin Air Quality

Pressurization
Ventilation
Recirculation
Nonrecirculation
Air contaminants
Chemical
Biological
Air filtration
Temperature
Relative humidity

In the early days of airline operations, the ranks of flight attendants were made up of young women in their 20s and early 30s. Currently, the demographics of this workforce have changed to include much older employees. Actual sensitivity to air quality or the perception that air quality is adequate may have changed with this population at risk.

Physical Factors

Environmental control systems must provide a safe and comfortable cabin environment despite cruising at altitudes in excess of 12,000 m. Pressurization, temperature regulation, airflow, and filtration are necessary elements of the aircraft environmental control system. By Federal Air Regulation (FAR), cabin pressure altitude cannot exceed 2,438 m (8,000 ft). The basis for this level was the oxyhemoglobin dissociation curve, given the assumption passengers are healthy, normal individuals and would be capable of maintaining a saturation of 90%. Although this assumption might have been valid when air travel was in its youth, currently the spectrum of passengers is broader, regularly including the sick and elderly.

To accomplish a suitably pressurized cabin, air is compressed by the aircraft engines and bled off from one of the compressor stages to the environmental control system. Heated significantly due to the compression (Charles' law), the air must be cooled by heat exchangers and an air-conditioning system to reach a comfortable temperature range (36). Airflow is continuous and laminar, moving side to side across sections of the cabin. This design element is important in understanding airborne communicable disease transmission in aircraft. Fresh cooled air combines with an equal amount of recirculated, highly filtered cabin air. The high-efficiency filtration system captures dust, allergens and other particulates, and most airborne microbes. Odors tend to be quickly diluted due to the continuous airflow, which can provide more than 20 cabin air changes per hour—a generous exchange rate compared to those seen in office buildings.

The astute reader may question why half of the cabin air is filtered and recirculated, when it would be entirely possible to provide 100% of the intake air from the compressor duct. In fact, older aircraft employ this very construct because their engine design produces most of its thrust from the engine core. Extracting all of the cabin airflow from the compressor had only modest impact on fuel economy. However, newer designs employ high bypass ratio fans that move most air around the core of the engine instead of through it. Most of the thrust is provided by the bypass air. On this type of engine, tapping air from the engine core significantly decreases fan thrust and impacts fuel efficiency (36). A compromise is struck with partial recirculation in order to balance fuel consumption, environmental emissions, and cabin air quality. Because the inflow air at altitude is very dry, another benefit derived by recirculating part of the cabin air is a modest increase in relative humidity. Relative humidity levels often drop below 5% on long duration flights (33).

Chemical Contaminants

Just as with any indoor environment, an aircraft possesses a variety of sources of volatile organic compounds (VOCs). Painted surfaces, fabrics, and carpets may off gas especially when they are first brought into service. Cleaning products, as well as food being handled and heated, can contribute to cabin volatile organics. The ventilation system is usually free of VOCs because the compressor stage source is taken before air enters the combustion chamber. In the setting of a mechanical failure such as a seal leak, contaminants could enter the ventilation system but would quickly be recognized as an in-flight emergency with odor and probably smoke or fumes in the cabin.

Carbon Dioxide

The primary source of carbon dioxide in an aircraft is the respiratory exhalations of the crew and passengers. With adequate environmental control system ventilation, levels of CO_2 remain well under concentrations associated with adverse health effects or performance decrement. Subsequently, carbon dioxide levels can be thought of as an indicator of the adequacy of ventilation.

Normal outside air at the surface contains approximately 380 ppm (0.03%) carbon dioxide (rising from a pre-Industrial Revolution level of 280 ppm). Human ventilation rates increase if the inhaled CO_2 concentrations reach 20,000 ppm (2%) and health effects such as dyspnea, dizziness, and slowed mentation would not be expected until approximately 60,000 ppm (6%) (37). FAR 25.831 establishes the FAAs standard for cabin CO_2 as 5,000 ppm (0.5%). Air quality studies have not identified high carbon dioxide levels in flight (32).

Another potential source of carbon dioxide aboard aircraft is in the sublimation of dry ice used as a refrigerant for perishable goods. In 1998, while taxiing to takeoff, all four crewmembers of a DC-8 freighter became dyspneic (38). Donning oxygen masks, they safely returned to the terminal without incident. The cargo included 960 lb (198 4.85 lb blocks) of dry ice in the main cargo bay to ship frozen shrimp. Following this incident, National Transportation Safety Board (NTSB) asked the FAA to reexamine its maximum dry ice allowance based on cabin volume. Since the original studies on sublimation rates, which demonstrated 1% per hour, dry ice preparations have morphed from 100 lb blocks to small, several pound pellet forms. A subsequent FAA study found the pellet form of dry ice to have a sublimation rate twice as high as the older block form (39). Aircraft volume and air exchange rates are then used to determine a safe limit for onboard dry ice.

Carbon Monoxide

Any source of unintentional combustion aboard an aircraft has the potential to introduce carbon monoxide into the cabin. Obviously, the engines are the primary potential source for this serious toxin, but as was discussed previously, it would be unlikely for engine emissions to find their way into the ventilation system without immediate notice. Cabin air quality studies have not documented unsafe levels of carbon monoxide under routine conditions. FAR 25.831 establishes a CO cabin limit of 1 part in 20,000 (0.005%). However, small aircraft with reciprocating engines may introduce CO into the cabin through leakage by the heating system.

Ozone

Ozone, a triatomic allotrope of oxygen, is a clear blue gas that is naturally formed when ultraviolet (UV) light interacts with stratospheric oxygen. Molecular oxygen photodissociates, freeing an oxygen atom that can combine with another molecule of oxygen to form ozone. Ozone itself can be dissociated by UV light back to oxygen. This oxygen–ozone forming and dissociation cycle has the effect of absorbing solar radiation and heating up the atmosphere. The presence of ozone in the lower stratosphere (LS) and upper troposphere (UT) is essential to life on Earth because of its properties in filtering out harmful UV radiation. It is a potential contaminant aboard aircraft, entering through bleed air at cruise altitudes. Stratospheric ozone concentrations vary according to altitude, latitude, season, and low pressure systems—with levels highest in the northern hemisphere during late winter and early spring. High-altitude military reconnaissance aircraft must routinely deal with this cabin contaminant by staying on supplied air.

Ozone is a respiratory irritant with mild exposures leading to eye, nose, and throat irritation, chest tightness, and headache that typically resolve with cessation of exposure. Studies have associated ozone exposure with decreased lung function, exacerbation of asthma, and immune system impairment (40–43). The FAA, in FAR 25.831, has set the standard for cabin ozone at 0.25 ppm (sea level equivalent) at any time above 9,750 m (32,000 ft.) There is also a 3-hour time-weighted average of 0.100 ppm over a 3-hour period when above 8,250 m (27,000 ft.) Studies of cabin ozone level have shown a minority of long duration, late winter/spring flights may exceed the FAA limit (32,44). Some carriers provision their aircraft with ozone converters, which can effectively neutralize this hazard.

Allergens

As with any indoor environment, particulates of dust, pollen, fibers, hair, and hair products may be present in the aircraft. Passengers allergic to such substances benefit by new air being constantly introduced into the cabin and particulates being trapped by high-efficiency particulate atmosphere (HEPA) filtration. Passengers with severe food allergies may be at risk if the food is served and consumed by fellow occupants, although exposure through inhalation or contact tends to lead to less severe reactions.

Communicable Disease

The influence of air travel and infectious disease spread has been the subject of investigations for many years. The International Civil Aviation Organization (ICAO) forecasts that by 2015 more than 2.5 billion people will travel by air each year. The potential impact on the spread of infectious disease may be substantial, for example, discussions of a possible avian influenza pandemic invariably include the role of air travel in exacerbating spread (see Chapters 19 and 28 for additional information).

During a recent investigation of travel-related severe acute respiratory syndrome (SARS), patients meeting the case diagnosis of cough, difficulty breathing, and fever, plus a close contact with a SARS patient or stay in an area with epidemic SARS, had respiratory samples tested by polymerase chain reaction. Thirty percent of samples were positive for influenza or parainfluenza virus (45). Minority percentages (all <5%) were represented by adenovirus, coronavirus, rhinovirus, and human metapneumovirus.

Because most diseases have incubation periods longer than the duration of air travel, transmission probably occurs more frequently than is reported. For example, common cold outbreaks as a result of air travel have not been reported. Large droplet and airborne mechanisms probably represent the greatest risk because of the density and close proximity of passengers (46).

Tuberculosis

Passengers with active pulmonary tuberculosis (TB) may travel on an aircraft without being aware of their diagnosis. Although screening for the disease is required for immigrants or refugees, tourists or business travelers may travel from an endemic country without obligatory screening. TB infection is acquired through inhalation of aerosolized respiratory secretions containing *Mycobacterium tuberculosis* as a result of coughing, sneezing, or talking. Risk of infection is dependent on the particular virulence of the pathogen, duration of exposure, proximity to the infected person, ventilation of the cabin, and density of occupancy. The latency between acquiring infection and developing active disease ranges from 2 weeks to many years. Although *infection* has occurred, no case of *active* TB has been identified because of exposure on a commercial aircraft (47).

Contact investigations between 1992 and 1994 involving seven highly infectious index patients (a cabin crewmember and six passengers) expanded to 2,600 potentially exposed passengers and crewmembers across 191 flights. There was evidence of TB transmission in two of the investigations. In one, the infected cabin crewmember passed infection onto other crewmembers in which there was at least 12 hours of exposure time. In the second, an infected passenger passed infection to other passengers seated in the same section of the plane and in close proximity (48).

The WHO's TB and Air Travel Guidelines for Prevention and Control, Second Edition provides a series of recommendations to reduce the risk of passengers being exposed to TB on aircraft. Passengers and aircrew with infectious TB must postpone long-distance travel until they are noninfectious. The WHO guidelines direct physicians to inform their infectious TB patients to wear a mask if they must travel, not to travel on long-duration flights until completing 2 weeks of adequate treatment, or in the case of multidrug resistant tuberculosis (MDR-TB), not fly until demonstrating negative cultures. Public health authorities are to contact the involved airline, if aware that a person with infectious TB is known to have flown in the past 3 months on a long-duration flight. They are additionally charged with promptly contacting potentially exposed passengers and crew. Recommendations for airlines include the denial of boarding to any person known to have infectious TB intending to travel on a long-duration flight, minimizing ground delays to less than 30 minutes with the ventilation system turned off, and ensuring HEPA filters are changed regularly. Airlines must ensure crews are trained in the use of universal precautions and stock aircraft with gloves, masks, and biohazard disposal bags.

While this chapter was in preparation, an international incident occurred when a U.S. citizen traveled to Europe and returned while infected with drug resistant TB. Although his degree of infection was uncertain, there was consensus that he carried extensively drug resistant tuberculosis (XDR-TB) later corrected to MDR-TB. Multiple countries and airlines were involved in the alert. Hundreds of passengers were located and contact follow-up was recommended. Upon return to the states, the traveler was hospitalized and quarantined. The degree of secondary case infection, if any, is unknown at this time (2007). The incident has resulted in an extensive review of airline and CDC policies related to transport of infectious passengers aboard aircraft and modern day issues regarding quarantine.

Influenza

Many of the principals discussed for TB can certainly apply to influenza, as well as other infectious diseases. This acute viral disease of the respiratory tract is spread predominantly by large droplets. Symptoms may develop rapidly in a patient—potentially after an apparently healthy passenger has boarded an aircraft. Air travel can serve as a vehicle for the global spread of influenza and transmission can occur aboard aircraft. An influenza outbreak occurred in 1979 among passengers on a flight that had been delayed for 3 hours on the ground. The plane's ventilation system had been turned off for the delay, removing the benefits of laminar flow. The attack rate among the passengers was 72% (49).

The influence of air travel on the spread of influenza has been studied using computer simulations. Such simulation studies have concluded that air travel restrictions may not have a significant impact on the course of a pandemic. In a recent empiric study looking at evidence for the effect of air travel on influenza spread, the rate of inter-regional spread and timing of influenza in the United States was compared to air travel. The study period (1996–2005) included the hiatus in air travel following the September 2001 terrorist attacks, providing a natural experiment for the evaluation of flight restrictions. This study found domestic airline travel volume in November correlated with the rate of influenza spread and international airline travel influenced the timing of influenza mortality. The 2001 to 2002 depression in travel volume was associated with a delayed and prolonged influenza season (50).

Severe Acute Respiratory Syndrome

SARS emerged onto the international headlines in 2003 as air travel rapidly expanded an epidemic in Hong Kong to areas around the globe. Subsequent investigations looked at transmission of the illness where patients with laboratory-confirmed SARS-corona virus were known to have flown. In one flight from Hong Kong to Beijing carrying a symptomatic passenger, transmission was shown to have occurred to travelers sitting in the same row as the index case or within three rows directly in front of him (8 of 23 passengers) (51).

The laminar flow pattern of cabin ventilation and HEPA filtration appear to have aided in constraining further spread of the virus. The distribution of those infected around the index case also suggests disease transmission by small droplet or aerosol. For flights that were shown to have carried infected passengers, but were asymptomatic at the time of travel, no transmission was noted. In one study with five index SARS patients who reportedly flew *with* symptoms, no transmission was found among 312 potentially exposed fellow passengers (52). The primary preventive strategy against in-flight transmission is to attempt to forbid symptomatic SARS patients from traveling. Guidelines for commercial air travel and air medical transport relevant to SARS were published by the Aerospace Medical Association in 2004.

Quarantine

Enforced isolation of individuals for the containment of disease spread has been effectively employed since ancient times. Societies understood the infectious nature of leprosy and advocated the isolation of lepers from the nondiseased. The term *quarantine* is derived from the Italian *quaranta giorni*, meaning 40 days—the usual time employed for early quarantine, probably derived from the duration of time Christ spent in the desert wilderness. It was the city of Venice that instituted the world's first institutionalized system of quarantine. In an effort to save the city from the Black Death, a council was empowered to detain ships, cargo, and people in the Venetian lagoon for up to 40 days (53).

From the 1400s onward, plague, yellow fever, and cholera epidemics were fought off with enforced quarantines in many seaports and major cities of the world. In 1851, after epidemics of plague and cholera from Egypt and Turkey spread through Europe, the first international sanitary conference was held in Paris. Germinating out of subsequent conferences, the International Office of Public Health was instituted, followed by the League of Nations Health Office. In 1948, the United Nations established the WHO.

The first sanitary convention for aviation occurred in 1933, addressing problems of infectious disease control, sanitation, and medical inspection. The WHO created a committee on Hygiene and Sanitation in Aviation, charging it with the development of guidelines to protect the international community from aircraft-associated disease importation. An updated Guide to Hygiene and Sanitation in Aviation is currently under progress. The original guide dates back to 1977.

The subject of quarantine is not only an historic subject. In 2003, the containment of SARS was credited to isolating the sick and quarantining the exposed. President Bush added SARS to the list of quarantinable diseases to join plague, yellow fever, cholera, smallpox, diphtheria, viral hemorrhagic fevers, and infectious TB. Quarantine is commonly discussed as a necessary control in the context of managing a biological terrorist attack. The subject also invariably raises the issue of infringement on individual civil rights. Such concerns will need to be balanced against the interests of the general welfare of the community—that is the public health.

Quarantine is also very relevant to space operations. Before a mission, astronauts are placed in medical preflight seclusion to minimize their exposure to pathogens that could lead to in-flight illness. After the Apollo missions, crews were placed in a mobile quarantine trailer at touchdown and transported back to Houston. Lunar specimens were handled as potential biohazards and quarantined in Johnson Space Center's lunar receiving laboratory for several weeks. Formal quarantine procedures will play a vital role in interplanetary missions in the future. With the possibility of an unmanned Mars mission in the near future, a quarantine facility will need to be constructed. That facility will need to be capable of biological containment to protect the earth from potential martian pathogens, and of preventing terrestrial microbes from infiltrating the martian samples.

International Health Regulations

The WHO revised the International Health Regulations (IHRs) in 2005. This was the first revision of the IHRs since 1969 and represented a major decision in the use of international law to protect public health. A key element of the revision was the establishment of a global surveillance system that could detect public health emergencies having potential international impact. The surveillance system articulated by the IHR 2005 includes health-related events under surveillance, purpose and objectives of the system, components and processes of the system, and required resources (54).

Events under surveillance include any that "may constitute a public health emergency of international concern." This new definition expanded from the 1969 list of three communicable diseases and keeps the door open for newly encountered disease, communicable or noncommunicable, naturally occurring or acts of bioterrorism. Any unexpected or unusual public health event might suffice under this definition. The IHRs address inclusion of exported or imported human cases of disease, disease vectors, or contaminated goods.

The stated purpose of the surveillance is to prevent the international spread of disease. Diligent, active surveillance by member state parties is vital in achieving this objective. Core surveillance capabilities and timely dissemination of trends will facilitate cross-border public health responses. Each member must develop capabilities to detect, assess, and report public health events from the local, regional, and national level to the WHO. Development of such capabilities may prove to be the most difficult challenge in developing countries short on resources (55).

Sanitation

Maintaining sound aircraft and airport sanitation are important facets of health promotion. The WHO designates an airport as an "international sanitary airport" after assessing its food and water quality, environment, sewage treatment, garbage disposal, and health facilities. Capabilities of the health facility must include prompt isolation and care of infected persons, disinfection, disinsection, deratting, and available laboratory support.

As new health issues arise, implications for aircraft and airport sanitation need to be anticipated. As an example, CDC issued guidelines and recommendations for cleaning aircraft exteriors after collisions with birds in avian influenza A (H5N1)-affected areas. Guidelines included avoidance cleaning methods that might aerosolize carcass remnants.

Food-borne Disease

Food-borne outbreaks are certainly not unique to air travel and can occur whenever a group of people eats pathogen-contaminated food. The CDC estimates approximately 75 million Americans contract food-borne illness each year—300,000 requiring hospitalization. Common pathogens include *Campylobacter, Salmonella*, *E. coli* O157:H7, Norwalk-like virus, and the preformed toxin from *Staphylococcus aureus* growing in food. Historically, the classic setting for a food-borne illness outbreak was a picnic meal or banquet dinner. Over the last decades fruits, vegetables, nuts, cereals, and snack foods contaminated with *Salmonella* or *E. coli* have been distributed regionally or nationally and implicated with large-scale illness. Transmission of food-borne disease on aircraft has been amply documented and includes *Salmonella*, Staphylococcal toxin, *Shigella*, and cholera.

In an effort to save money, airlines have tended to serve fewer meals domestically. Hot meals are still served in transoceanic flights or long-duration continental flights, whereas prepackaged cold snacks are most commonly served aboard intermediate length flights. In all cases, food quality, preparation techniques, storage, and elapsed time between preparation and consumption foreshadow the likelihood of food contamination.

In 1975, approximately 57% of the passengers aboard a commercial aircraft contracted an acute gastrointestinal illness. Approximately 150 passengers and a flight attendant required hospital admission. Investigation of this largest ever food-borne outbreak aboard an aircraft strongly incriminated ham handled by one particular cook with finger lesions (56). Stool, vomitus, leftover food, and skin lesion specimens were positive for identical phage type *S. aureus*. Preformed enterotoxin was detected in leftover ham and omelette. This toxin has a short incubation period of only a few hours.

In a review of food-borne illness aboard aircraft from 1947 to 1984, Tauxe et al. studied 23 outbreaks and identified *Salmonella* as the most common pathogen, followed by *Staphylococcus* and *Vibrio* species. Not surprisingly, outbreaks were most often due to improper temperature preparation or storage (57).

In 1988, confirmed or probable shigellosis was diagnosed in 240 passengers on 219 flights across 24 states and several countries (58). The index outbreak occurred in a professional football team, which facilitated prompt identification and investigation. An outbreak-associated strain of *Shigella sonnei* was isolated from football players and staff, airline passengers, and flight attendants. A common source was traced back to eating cold food items served on the various flights that had been prepared by hand at a Minnesota-based airline flight kitchen.

In 1992, a flight from Buenos Aires and Lima to Los Angeles provided passengers with Vibrio-contaminated seafood salad (59); in 75 of the 336 passengers on board eventually demonstrated stool positive *Vibrio cholerae* serotype 01 (60). This case of airline-associated disease transmission represented the largest outbreak of cholera of the 20th century in the United States. At the beginning of this section, it was stated that food-borne illness is not unique to air travel. Unlike the picnic or banquet dinner setting, aviation-associated food-borne disease includes the rapid and wide dissemination of passengers following their becoming infected. In addition, many of these outbreaks, involving a plane full of transient strangers, may have occurred and gone unnoticed.

Vector-borne Disease and Disinsection

Vector-borne diseases pose a risk for approximately half of the world's inhabitants. Although there are long-known endemic areas of such disease, there are also areas susceptible to introduction or reintroduction of vectors and pathogens. Even without the effect of international travel, one potential effect of global climate change is enlargement of vector-borne disease regions. Malaria, dengue, and leishmaniasis are leading examples of vector-borne diseases of importance to air transport in both cargo and passenger-carrying vehicles. To protect against importing insects capable of transmitting disease, the practice of eradicating insect vectors by spraying pesticide is routinely carried out by airlines (61–63). Disinsection is sanctioned by international law and is governed under the guidelines published by the WHO's IHR.

The decision to routinely perform aircraft disinsection is left to individual countries. Over the years, many countries have discontinued the practice secondary to health concerns of the cabin occupants as well as questioned efficacy in controlling disease. Routine disinsection was discontinued in the United States in 1979, but a number of countries still require the practice on all in-bound flights.

Sanctioned methods of disinsection have been articulated by the WHO and ICAO. The 2005 IHR (adopted in 2007) mandates reporting any public health threat potentially posed by imported or exported vector borne disease. Specific measures for vector borne disease are covered in Annex 5. The principal difference among approved methods is the timing of pesticide application. The most common and recommended is referred to as *blocks away* disinsection, in which an aerosol is sprayed throughout the cabin as it leaves the gate. To be optimally effective, cabin ventilation should be turned off and all galleys, toilets, lockers, and overhead compartments need to be sprayed. As actual practice deviates from this ideal, efficacy of disinsection obviously decreases. Other disinsection methods include prespraying before passengers board, then spraying the cabin just as final descent is initiated or upon arrival at the flight's destination, before deplaning. To completely avoid spraying pesticide while passengers are onboard, an alternative method is to periodically apply the agent to the aircraft's surfaces during scheduled maintenance—known as *residual disinsection*.

The only class of pesticides approved for disinsection is the pyrethrins, and the synthetically derived pyrethroids. Single-shot aerosol cans of permethrin or d-phenothrin (2%) are most commonly used. Spent aerosol cans provide evidence for airport authorities verifying that disinsection was carried out. Cabin crewmembers have complained of itching, rashes, headache, sore throat, respiratory irritation, and tingling of fingers and lips that they have associated with the application or residuals of pyrethroids. However, studies have not supported a cause–effect relationship of these symptoms to aircraft-based exposures.

Some argue against pyrethroid use on aircraft, questioning their safety of use in proximity to children and asthmatics in the closed space of an aircraft (64). A 2003 study assessed neurobehavioral function in self-identified flight attendants exposed to pyrethroids compared to a control group. The exposed group performed significantly worse on testing of balance, grip strength, and color discrimination (65). The National Research Council mentioned pesticides as a health concern in its 2002 report on the airliner cabin environment, noting they had not been monitored adequately to assess potential health risks.

Occupational (agricultural) exposures in high enough concentrations to cause systemic neurologic symptoms have occurred, but patients have recovered quickly once removed from the agent. Research studies looking at the dermal toxicity of pyrethrins and pyrethroids have demonstrated low toxicity. The widespread use of pyrethrins and pyrethroids in shampoos and rinses for treating scabies and lice makes for a large "exposed" population without significant numbers of adverse effects (66).

Although the practice of routine disinsection may be decreasing, it would not be wise to discount the potential role of aviation in spreading vector-borne disease. The most direct evidence of vector-borne disease transmission by aviation is the example of airport malaria. People who have had no travel history to malaria endemic areas, no history of blood transfusions, but have lived near an international airport receiving flights from malaria endemic countries have acquired the disease in France, Belgium, the United Kingdom, Luxembourg, the United States, and in other countries. Because malaria is not initially included in the differential diagnosis in such cases, the reported numbers in the literature are probably low. Separate episodes of malaria involving five patients living within a few kilometers of Luxembourg International Airport during the summer months of 1997 and 1999 would indicate infected mosquitoes brought in aboard aircraft from Africa were able to fly around the local vicinity and subsequently infect local inhabitants (67).

An even less common manifestation of aviation-related disease transmission is called *runway malaria*. Passengers traveling between two nonendemic countries had *en route* stopovers in tropical Africa and subsequently developed *Plasmodium falciparum* malaria. In these cases, passengers or crewmembers had remained seated in the aircraft at Abidjan Airport, Cote d'Ivoire or Banjul Airport, Gambia, with open doorways for 1 to 2 hours. Of note, disinsection was performed after leaving the gate on at least one of these flights (68).

COMMUNITY AND GLOBAL ENVIRONMENT

Jet Engine Emissions

To provide thrust, aircraft engines combust fossil fuel producing gases and particulates secondary to that process. Roughly speaking, aircraft engine emissions are 70% carbon dioxide, 29% water, and less than 1% nitrogen oxides, carbon monoxide, sulfur oxides, unburned hydrocarbons, and particulates. Standards for jet emissions are established by the EPA. The FAA is then responsible for enforcing the standards. Although similar to car exhaust, jet emissions largely occur at altitude. How this difference impacts the true contribution of aviation to the global environment is still unclear to atmospheric scientists, but parameters such as atmospheric dwell times and vertical mixing clearly affect such impact. Global carbon dioxide levels are increasing and known sources of generation include aircraft emissions of carbon dioxide representing 2.5% of total fossil fuel emissions in 1992 (69). Aircraft emissions at altitude also trigger the formation of condensation trails and may increase cirrus cloudiness. A concept used in estimating overall global impact is that of radiative forcing—the change in average net radiation at the top of the troposphere based on the balance of incoming solar radiation versus outgoing infrared radiation. The Intergovernmental Panel on Climate Change (IPCC) estimates the contribution of aviation to total radiative forcing (warming) by all human activities to be approximately 3.5%.

Jet engine emissions near airport operations remain an important consideration. As engine technology has improved over the past years, so have emission levels, but this may be more than offset by the increase in aviation volume. In the vicinity of airports, emissions of concern include unburned hydrocarbons, carbon monoxide, and oxides of nitrogen. Airport access, ground support vehicles, and auxiliary power units also produce similar emissions into the local atmosphere. The EPA estimates that aircraft engines contribute approximately 1% of the total U.S. mobile source NO_x emissions, but in the vicinity of airports, this contribution is approximately 4% (70). Elevated levels of oxides of nitrogen create smog and increase surface ozone concentration, a pulmonary irritant. The Clean Air Act requires EPA to determine if areas comply with the National Ambient Air Quality Standards. Ozone is by far the principal air quality problem in U.S. cities with 37 of the country's 50 primary airports in nonattainment areas for ozone (71).

Ozone Depletion

Ozone was discussed previously as a potential contaminant of aircraft cabins, where it can pose a pulmonary and mucosal irritant hazard to inhabitants. Ozone is naturally present in the upper stratosphere where it provides beneficial shielding against UV radiation reaching the earth's surface. If a given column of atmospheric ozone were compressed at standard temperature and pressure (STP) at sea level (1 STP), the resulting concentrated layer would only measure a few millimeters in thickness. Atmospheric ozone is measured in Dobson units, in which one unit is equivalent to 0.01 mm at 1 STP (Figure 21-2).

Ozone is unevenly distributed in the atmosphere and seasonal variations are noticeable. However, between 1977 and 1984 satellite imaging, balloon, and aircraft sampling detected a 40% decrease in the ozone layer overlying Antarctica (72). As knowledge was increased on atmospheric ozone, it was discovered that there is a large, but seasonally related decrease in stratospheric ozone over the Earth's polar regions. More worrisome perhaps is that a slow, steady decline of total ozone in the atmosphere has also been observed, occurring at a rate of approximately 4% per decade (Figure 21-3).

The detailed mechanism by which the polar ozone "hole" forms is different from that for the mid-latitude thinning related to the extremely low temperatures possible in Antarctica. However, the most important process in both trends is the catalytic destruction of ozone molecules

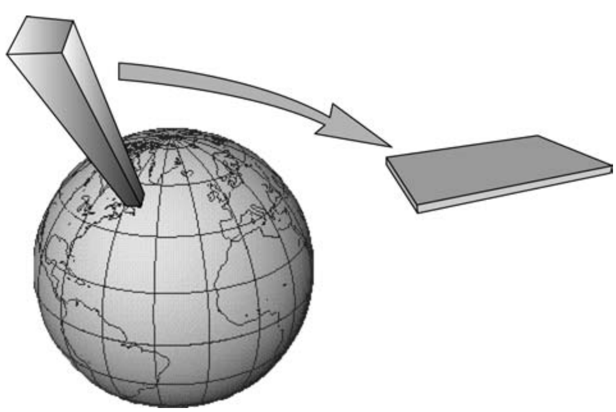


FIGURE 21-2 The Dobson unit is derived by defining a vertical column of ozone in the atmosphere and compressing it into a horizontal slab at standard temperature and pressure (0° C and 760 mm Hg). A slab compressing to 3 mm thickness would correspond to 300 Dobson units.

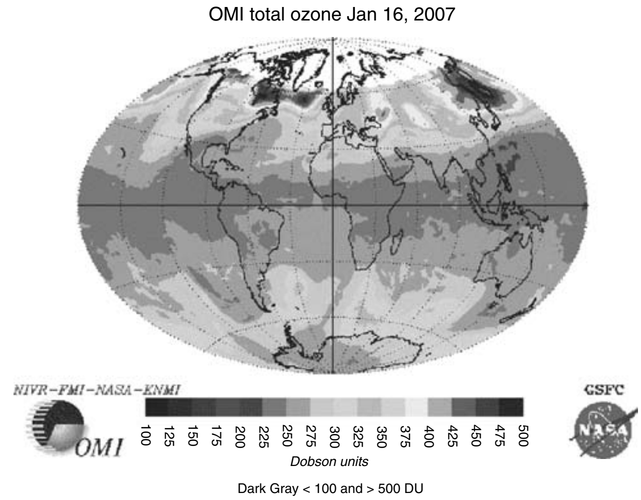


FIGURE 21-3 Satellite sensor data demonstrating distribution of global ozone concentration in mid January. OMI, ozone monitoring unit; CSFC, Commitee of State Financial Control. (Courtesy of NASA.)

by atomic chlorine and bromine. The main source of halogen atoms in the stratosphere is from *surface* release of chlorofluorocarbon compounds and bromofluorocarbon compounds. Although these compounds are heavier than air, they work their way up to the stratosphere and photodissociate into chlorine or bromine atoms. (The need for light energy explains the seasonal nature of the Antarctic ozone "hole.")

If stratospheric ozone decreases, absorption of incoming UV radiation decreases and more of it is able to reach the surface. This becomes especially concerning for ultraviolet B (UVB) wavelengths (270–315 nm). Increased incoming UVB radiation at the Earth's surface could pose serious biologic effects for the planet. Harm to oceanic plankton, harm to land plants, and increased incidence of actinic skin damage, skin cancers, and cataracts are a few of the possible consequences of ozone depletion.

Jet engine emissions produce a number of chemically active species that have the potential to affect atmospheric ozone concentration. According to the IPCC, a scientific panel established by the World Meteorological Society and United Nations Environment Programme, engine emission species having the greatest potential impact are nitrogen oxides, sulfur oxides, soot, and water. In the troposphere and LS, ozone concentrations *increase* in response to oxides of nitrogen and *decrease* in response to water and sulfur. Although soot particulate has the capacity to decrease ozone, the emitted concentration of soot is so low; this property is not thought to be significant. Unlike halogen atoms, soot particles do not propagate a catalytic destruction of ozone. At the upper levels of the stratosphere, ozone concentrations *decrease* in response to oxides of nitrogen.

Aircraft emissions are believed to have increased the concentration of oxides of nitrogen at cruise altitudes in the northern mid-latitudes by 20%. This change is not as dramatic as it first sounds when considering the variability observed in atmospheric NO_x and the vertical movement of nitrogen oxides. Jet engine NO_x emissions are small compared to fossil fuel burning at the surface and oxides of nitrogen are additionally formed naturally by lightning in the troposphere.

In its 1999 report titled "Aviation and the Atmosphere" the Intergovernmental Panel on Climate Change states:

> "In summary, because the database for ozone observations in the UT (upper troposphere) and LS (lower stratosphere) is still relatively limited and because uncertainties in observational data, as well as model representations of non-aircraft ozone forcing phenomena, are quite large, it is presently impossible to associate a trend in ozone to aircraft operation with meaningful statistical significance."

Understanding ozone depletion has required a great deal of work in unlocking the complexities of atmospheric chemistry—leading to at least one Nobel Prize. Appreciating the true impact aviation may have on this subject will need to wait for future editions of this textbook.

Alternate Fuels

Current jet fuels are a blend of hydrocarbon saturates, aromatics, and various additives. Although there are differences in specifications across the spectrum of civil and military fuels having to do with a desired freezing point, flash point, thermal stability, or volatility, all are nevertheless kerosene-type refined petroleum products. Although the price of jet fuel is tied to the crude oil market, it has risen disproportionately over the last several years, making fuel cost the largest operating expense for U.S. airlines (73). In the short term, there are concerns over volatility in the petroleum market related to geopolitical forces. In the longer term, as petroleum consumption continues to climb, global supply capacity may be overtaken by demand.

Initiatives striving to develop alternatives to traditional crude oil–based jet fuel will need to deal with operational, financial, and environmental consequences. Biomass conversion and coal-derived fuel are examples of potential alternatives. However, any proposed alternate fuel source will need to be assessed against the balance of properties currently afforded by kerosene-type fuel. Energy density, safety, operational issues, cost, and emissions differ significantly across potential fuel candidates.

Noise

Noise is the term we apply to any unwanted sound or sound pollution. It is an important issue both occupationally and environmentally. Noise is an unfortunate, yet fundamental characteristic of aircraft operations. Turbojet, turbofan, turboprop, and piston engines all generate considerable noise levels. This noise is especially problematic near takeoff and landing patterns. Cities have had to make choices of placing their airports at locales close enough to conveniently serve the intended population versus keeping them in relatively remote areas to mitigate unwanted noise. Even in cases in which airports were built away from dense population areas, urban sprawl has in many cases eventually brought the city to the perimeter of the airport. Additional information may be found in Chapter 5.

Noise Measurement

Sound is our perception of acoustic energy. Owing to the large range of acoustic wave amplitude the ear is capable of hearing across; it is useful to employ a logarithmic decibel amplitude scale. With such a scale, a 20-dB noise level is ten times greater than a 10-dB noise. A 36-dB sound is twice as loud as a 33-dB sound. If a machine generates 62 dB of noise, turning on two such machines would be expected to generate 65 dB. A typical conversation is approximately 60 dB. When we are around noise loud enough to compel us to shout to converse with someone approximately 3 ft away, we are approaching 85 dB, which is defined as hazardous noise. Prolonged exposure to noise levels exceeding 85 dB can permanently damage the ear and cause sensorineural hearing loss and tinnitus.

Noise Effects

The effects of noise on physiology and health have been well described in the occupational literature. However, these data cannot be generalized to environmental exposure. There are few quality studies that have analyzed community health effects from aircraft noise. A problematic effect of noise is that of interference with spoken communication—referred to as *masking*. Social surveys have indicated that aircraft noise interferes with direct conversation, telephone use, radio or television use, and disrupts desired levels of quietness.

It probably comes as no surprise that interference with sleep due to aircraft noise generates more hostility and complaints than daytime interruptions. Communities tend to be much more sensitive to noise pollution during traditional sleeping hours, forcing many airports to alter their operations to provide "quiet hours" for the surrounding community.

Various composite noise indices have been developed to assess the impact of environmental noise in a community. The first composite noise rating (CNR) was introduced in the 1960s and was designed to evaluate land use near airports and predict annoyance levels secondary to airport operations. The measurement is based on maximum perceived noise level and frequency of day and night flights. Night flights are weighted 10-to-1 over day flights. A newer index, the noise exposure forecast (NEF) was developed by the FAA to predict community annoyance from aircraft operations utilizing an *effective* perceived noise level and similar weighting as the CNR. The effective perceived noise level takes into account tone components in aircraft noise and noise duration. Parameters such as seasonal corrections (effect of open windows, outdoor activities), outdoor residual noise levels, prior community experience with intruding noise, and pure tone versus impulsive character of noise may be added to the overall analysis.

Studies have examined the relation between environmental noise exposure and reading comprehension of children.

Retrospective studies may point to an effect of chronic noise exposure on reading, but may be confounded by the potential effects of acute noise exposure during testing. A pooled, multinational study reported a linear association between aircraft noise exposure at school and impaired reading comprehension (74). The association was maintained after adjustment for socioeconomic variables and acute noise annoyance.

Community surveys have linked aircraft noise to various physiological and psychological complaints. Studies have raised the question of possible associations between environmental aircraft noise and elevated levels of stress hormones and cardiovascular effects such as hypertension.

Noise Governing Guidance

The Convention on International Civil Aviation, also referred to as the Chicago Convention, requires all aircraft engaging in international operations to be issued a certificate of airworthiness. Part of that Convention (Annex 16) established standards for the control of aircraft noise. ICAO's Committee on Aviation Environmental Protection (CAEP) is responsible for environmental aspects of aviation and includes noise and engine emissions. The committee is charged with undertaking studies related to the control of aircraft noise. Two working groups under CAEP deal with the technical and operational aspects of noise reduction and mitigation. Before the committee can approve an increase in certification stringency, it must be able to meet economic reasonableness, technical feasibility, and prove an environmental benefit.

Sonic Booms

The term *sonic boom* refers to the air shock an object causes when traveling at the speed of sound. Although purposes of this text will discuss the sonic boom of supersonic aircraft and spacecraft, many other objects (flying or otherwise) are capable of creating this phenomenon. The crack of a bullwhip is created when the whip arc passes down the length of the leather and creates a miniature sonic boom. Thunder is the result of rapid heating and expansion of air due to lightning.

As an aircraft flies near the sound barrier, pressure waves similar to those seen around the bow of a boat begin to be forced together due to compression (Figures 21-4 and 21-5). The point at which these leading pressure waves merge into a single shock wave is at the speed of sound, or Mach 1, approximately 1,225 km/hr (735 mph) at sea level. The generated shock wave can yield tremendous sound energy in excess of 200 dB. Sonic booms are not well tolerated by communities and for this reason, supersonic flight is generally not authorized outside special use, for example, military operations areas.

Future Solutions for Aviation Noise

If a functionally silent aircraft were to be successfully designed and built in 1 day, the impact on airport operations volume, operating hours, and pattern proximity to residential areas could be considerable. The enabling technologies that would need to be developed would have to mitigate noise generation from the aircraft's propulsion system as well as that generated from the airframe. Engine design modifications will presumably need to work on reducing the exhaust jet speed. In order to quiet the engine, yet maintain sufficient thrust, the engineering challenge would be to somehow enlarge the engine exhaust area without dramatically compromising on engine size and weight. A joint research venture between Massachusetts Institute of Technology (MIT) and Cambridge is looking at designs that blend fuselage and wings together, optimizing airframe lift. This property could allow for lower power settings in landing

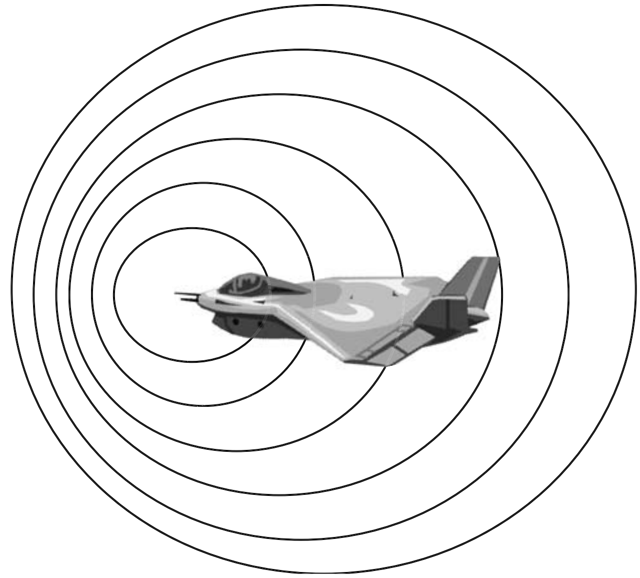


FIGURE 21-4 Subsonic flight demonstrating compression of pressure waves in front of aircraft.

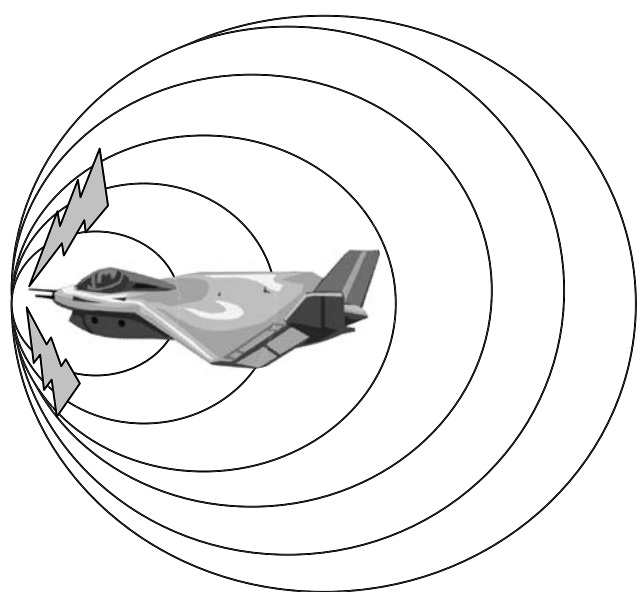


FIGURE 21-5 Mach one flight demonstrating merging of pressure waves into single large shock wave.

and takeoff phases, thereby decreasing noise generation. Interestingly, the current tube and wing configuration of modern airframes largely came about due to safety concerns for engine fires. A burning engine mounted to a pylon is relatively isolated from the rest of the airframe.

Radiofrequency Radiation

Radiofrequency radiation (RFR) is a low energy form of NIR. RFR frequency extends from 3 KHz to 300 MHz and is extensively used throughout the aerospace industry. Microwave radiation is also employed in aviation and is of higher energy at 300 MHz to 300 GHz. Radio beacons, very high frequency omni-directional radio (VOR), and radar systems are examples of aviation-related devices that generate RFR. Although these sources are important to consider in an occupational medicine context, that is a ground crew is exposed to a radar beam when erroneously left on, RFR sources are far less significant when discussing environmental exposures. One reason for this is the fact that RFR field strength drops off rapidly with distance from transmitters. Permissible exposure guidelines for RFR are published by the American National Standards Institute C95.1. The standards are based on whole body exposure, are time weighted (maximum permitted exposure for unrestricted occupancy), and dictate whether areas near a transmitter require restricted entry. There appears to be no significant risk to the general public attributable to aviation-related RFR.

Cosmic Radiation

The earth is incessantly showered by IR from space—variously referred to as *cosmic radiation, galactic radiation*, or *cosmic rays*. The latter term is rather misleading because cosmic radiation particles arrive individually, not as a beam or ray of particles. Cosmic radiation consists of high speed charged or neutral subatomic particles of various energy levels. The vast majority of particles are protons, followed by α particles and rare heavier nuclei and electrons.

Astronomers and physicists believe that the radiation originates from within the Milky Way galaxy from rotating neutron stars, supernovae, black holes, and our own sun (75). The incoming radiation collides with atmospheric molecules and produces lower energy secondary cosmic radiation. As one approaches the earth's surface, there are increasingly more gas molecules to collide with, eventually providing protection from all but the highest energy particles. For this reason, exposure to significant levels of cosmic radiation would be expected to occur at only the higher altitudes.

The incoming rate of cosmic rays onto the upper atmosphere is negatively impacted by the solar wind. Solar activity varies over an 11-year cycle, changing the intensity and expanse of magnetized plasma enshrouding the earth. Rarely, a solar proton event may cause an increase in cruise level radiation to aircrews and passengers. Cosmic rays are also attenuated by the earth's magnetic field. The lines of force of this field are nearly parallel to the surface of the earth near the equator and nearly perpendicular at the poles. Therefore, flights at higher latitudes can be expected to allow higher exposures to cosmic radiation than those in the tropics.

The FAA's Civil Aerospace Medical Institute has developed a computer program, named *CARI-6*, capable of computing the effective dose of cosmic radiation received by an individual on any particular flight. By inputting the date of flight, origin and destination airports, and involved altitudes, the program takes into account altitude, geographic location, the earth's magnetic field, and heliocentric potentials (solar activity cycle) then calculates an effective dose for any given flight.

The currently employed SI unit for expressing a radiation dose is the sievert. It is numerically related to the previously used roentgen equivalent man (rem) unit in that 1 Sv = 100 rem. The sievert attempts to reflect the biological effects of radiation, as opposed to the physical aspects characterized by the absorbed dose in grays. One important concept in the discussion of cosmic radiation exposure is that of proportionality given other sources of radiation exposure. Owing to terrestrial sources of radiation (radon, uranium), annual doses of IR at sea level could reach 2 to 3 mSv/yr. The commonplace use of diagnostic medical imaging studies further subject individuals to radiation. For example, a standard chest x-ray exposes an individual to approximately 0.1 mSv. Of course, this is a short duration, concentrated dose of radiation compared with the whole body exposure encountered in transoceanic flights diluted over many hours.

There are a number of relevant standards for IR exposure limits. The International Commission on Radiological Protections (ICRP) established a standard of 1 mSv/yr for the general public and 20 mSv/yr for nuclear industry workers, averaged over 5 years. A crewmember flying frequently and regularly at high latitudes and high altitudes would be subjected to the greatest annual cosmic radiation exposure. A representative dose equivalent rate from cosmic radiation at cruising altitude might be 5 mSv/hr. The average aircrew annual dose probably lies within 3 to 6 mSv, which is only a few times natural background. If future aircraft designs require significantly higher cruising altitudes (i.e., >21,000 m), health risks due to cosmic radiation may grow in significance.

Cumulative cosmic radiation exposure is so low, statistical power becomes a major concern in interpreting the literature. Studies looking at the effects of low-level doses of IR from all sources have centered largely upon cancer risk, although genetic and fetal harm have also been the subject of investigation. Research that has specifically looked for effects from cosmic radiation exposure in flight crews and flight attendants is more limited. When one considers the potential overlay of environmental exposures of aircrews to jet fuel, engine emissions, hydraulic fluid, radar, and so on the subject becomes even more complex.

Studies have looked for health effects due to cosmic radiation in military aircrew, airline pilots, and flight attendants (76). Whereas some studies have demonstrated a *reduction* in the expected incidence of some cancer types, incidence rates of some cancers that include non–melanoma and melanoma skin cancer and breast cancer were found to be increased (77–79). Expected versus observed cancer numbers within subgroups of aircrew studies tend to be small—often single digits (80). A large European flight attendant cohort study demonstrated no increased mortality attributable to cosmic radiation (81). A meta-analysis of cancer incidence among female flight attendants looked at cohort studies from 1966 to 2005 and confirmed increased risk for malignant melanoma and breast cancer among female flight attendants (82). Discussions of differences between female flight attendants and the general female population such as nulliparity provide alternative explanations to an occupational exposure (83). Skin cancer tends to appear in higher rates among aircrew and several authors attribute this finding to aircrew lifestyle and a greater opportunity to spend time sunbathing than the general population. A questionnaire by Rafnsson et al. attempted to identify malignant melanoma risk factors among aircrews, but failed to demonstrate identifiable differences between aircrew and the general public (78). Epidemiologic studies provide little consistent evidence linking cancer with radiation exposures in an aviation setting. Additional information may be found in Chapter 8.

Radio Isotope Generators

Cosmic radiation and solar events pose even greater potential risk to astronauts, who must operate completely outside the earth's atmosphere and potentially, outside the earth's magnetic field. Space radiation is one of the most significant hazards associated with orbital missions and will probably remain so with interplanetary missions. The reader is referred to the section on space environments for review on the subject. Another source of IR to consider is that generated by radioisotope thermoelectric generators. These generators contain plutonium-238 dioxide, which, through radioactive decay, heats a thermocoupler to generate electricity for a variety of spacecraft applications. Decay products are α-particles that are very easily stopped by even light shielding. The ceramic form of plutonium-238 was chosen for its properties of heat resistance, low vaporization, and tendency to not generate dust when fractured. NASA has gone to great length to enclose the plutonium pellets within three layers of protection and tested the system against fire, blast, ground impact, and immersion with good assurance of ruggedness.

Security Scanning

Technology has been employed for many years to provide security for aviation. Airport security provides a first line of defense against terrorists bringing weapons or bombs into an airport—greatly reducing the likelihood of such devices being brought onboard an aircraft. Screening of passengers, baggage, and freight tightened significantly after the terrorist strikes of September 2001 in which commercial planes were used as weapons. Metal detectors and gas chromatography for detecting volatile compounds given off by explosives are used routinely at airports. Standard x-ray tube fluoroscopy and computed tomography may be used to screen luggage. Physical distances, lead curtains, and administrative controls are employed to minimize exposure to radiation scatter. Radiation exposure is not considered a significant exposure to security workers. Risk to passengers or flight crews should be considered trivial.

More advanced x-ray machines utilizing backscatter technology are available to provide the equivalent of a strip search for passengers that require additional screening. Backscatter systems construct an image based on how various materials scatter x-ray photons. Organic materials feature much more specific scatter patterns than absorption patterns; therefore drugs and liquid explosives are visualized even if adhering next to body parts. The Health Physics Society estimates that a single backscatter scan delivers 0.00005 mSv to an individual (84). A frequent flyer, who might have to undergo the improbable number of 200 scans in a year, would only reach the negligible dose range of 0.01 mSv formulated by National Council on Radiation Protection and Measurements (NCRP).

ATMOSPHERIC CONCERNS

Contrails

Contrails are condensation trails that occur at high altitude due to water vapor being introduced by engine exhaust. The cold temperature and low vapor pressure at altitude causes the hot, humid air in the jet exhaust to exceed saturation, condense, and form ice crystals around particulate nuclei. Contrails may play a role in stratospheric and upper tropospheric chemistry. Depending on upper tropospheric winds and relative humidity, the formed contrail may dissipate quickly or persist for hours or more similar to a cirrus cloud. In a NASA satellite study, contrails were shown to last from 7 to 17 hours and some cases enlarge into 12,000 km^2 natural looking cirrus fields (85). In heavy air traffic corridors, the presence of large numbers of contrails can significantly contribute to cloud cover, potentially affecting the radiation balance of an area (Figure 21-6). This increased cloud cover both decreases incoming solar radiation (cooling effect) and reduces radiational cooling (warming effect).

During the September 11, 20013-day grounding of flights, researchers were able to observe the temperature effect in the absence of contrails. When compared to averaged 30-year historical temperatures across 4,000 weather stations across the continental United States, the days of the grounding demonstrated an average increased diurnal temperature range of 1.8°C—that is the lack of contrails appeared to make the days warmer and nights cooler (86).

Fuel Dumping

Some aircraft, especially large models optimized for long-distance flights, have a significantly higher maximum structural takeoff weight than permissible landing weight due to fuel storage. In the event the aircraft must land before it has consumed sufficient fuel to reach its landing weight, it

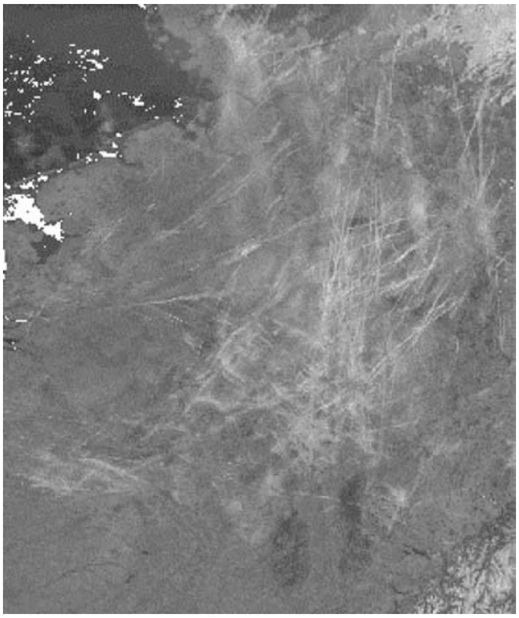


FIGURE 21-6 Satellite imagery demonstrating contrails over heavily traveled corridor in Europe (Photo courtesy of NOAA).

may need to jettison fuel in flight. This is not a routine event. From a purely economic basis, no airline is eager to dump thousands of gallons of jet fuel into the air. The development of a mechanical problem or passenger problem might force the flight to return to the airport or divert to another airport short of the destination.

Fuel dumping procedures are addressed in the FAA's Aeronautical Information Manual under emergency procedures and require coordination with Air Traffic Control (ATC). When a pilot decides to dump fuel, ATC broadcasts the event to area aircraft (87). VFR aircraft must clear the affected area and IFR aircraft are provided vectors to clear the area as needed. The aircraft jettisoning fuel is assigned an altitude at least 2,000 ft above the highest obstacle within 5 mi of route to ensure maximal evaporation (88).

Studies have looked at the fate of jettisoned fuel and have characterized droplet formation and evaporation. In ambient temperatures above freezing, fuel dumped above 1,500 m evaporates nearly completely—that is greater than 98% (89). In tests where fuel was jettisoned as low as 750 m at temperatures approximately 11°C, no liquid fuel could be detected by ground observers and sampling detected concentrations at only a few ppm (90). Any remaining fuel droplets and vapor are widely dispersed by atmospheric movement and turbulence, rendering hydrocarbon densities too low to create any perceptible environmental effect. In ground studies, obviously more applicable to fuel spills, there is ample evidence that jet fuel is biodegraded in soil.

ACKNOWLEDGMENTS

The authors were ably assisted in the production of this chapter by Ms. Jean Coppin. We wish to recognize the contribution of Dr. Mark Roberts, Dr. Al Parmet, and Dr. Claude Thibeault, who authored the impact of aerospace industry on environment and public health content in previous editions of this textbook.

REFERENCES

1. Ramazzini B. Diseases of workers. *The classics of medicine library, special edition*. Chicago: University of Chicago Press, 1983.
2. American Board of Preventive Medicine. *Occupational medicine defined*. www.abprevmed.org, January 2007.
3. Schulte PA. Characterizing the burden of occupational injury and disease. *J Occup Environ Med* 2005;47:607–622.
4. Green KB. *State of the art review*. *The Aviation Industry* 2002;17:2.
5. American Board of Preventive Medicine. *Physicians certified in specialties*. www.abprevmed.org, March 2007.
6. DeHart RL. Occupational medicine support for international air carriers. *Aviat Space Environ Med* 1990;61:67–70.
7. Hamilton A. *Exploring the dangerous trades*. Boston: Little, Brown and Company, 1943.
8. Dhenin G, ed. *Aviation medicine*. London: Tri-Med Books, Ltd., 1978.
9. U.S. Department of Labor, Bureau of Labor Statistics. www.dol.gov, September 2006.
10. American Airlines. *Occupational health report*. www.aa.org, January 2007.
11. BusinessWeek. *How delta is changing*. December 4, 2006.
12. DeHart RL. Guidelines for establishing an occupational medical program. *Am Occup Med Assoc* 1987.
13. American College of Occupational and Environmental Medicine. *Scope of occupational and environmental health programs and practice*. www.acoem.org/aboutACOEM.aspx, October 2006.
14. Aldana SE, Pronk NP. Health promotion programs, modifiable health risks and employee absenteeism. *J Occup Environ Med* 2001;43:26–46.
15. Bunn WB III, Pikelny DB, Slavin TJ, et al. Health, safety, and productivity in a manufacturing environment. *J Occup Environ Med* 2001;43:47–55.
16. American College of Occupational and Environmental Medicine. *ACOEM report*. OSHA/FAA to work together to improve flight attendants working conditions. Aug 2000.
17. American Conference of Governmental Industrial Hygienists. *Threshold limit values for chemical substance and physical agents*. Cincinnati: ACGIH, 2007.
18. Wald PH, Stave GM, eds. *Physical and biological hazards of the workplace*. New York: Van Nostrand Reinhold, 1994.
19. Zenz C, Dickerson OB, Horvath EP, eds. *Occupational medicine*, 3rd ed. St. Louis: Mosby–Yearbook, 1994.
20. Chaffin DB, Anderson GBJ. *Occupational biomechanics*. New York: John Wiley and Sons, 1984.
21. Air Transport Association. *Scientific advisory board meets to address pilot fatigue and alertness management initiative*. Press Release. 13 Dec 2000.
22. National Institute for Occupational Safety and Health. *Proposed national strategy for the prevention of work-related musculoskeletal injury*. *NIOSH Publication No. 8929*, Cincinnati, 1985.
23. National Institute for Occupational Safety and Health. *Guide manual lifting*. Cincinnati: NIOSH, 1993.
24. Pleil JD, Smith LB, Zelnick SD. Personal exposure to JP-8 jet fuel vapors and exhaust at air force bases. *Environ Health Perspect* 2000;108:183–192.
25. Boice JD Jr, Marano DE, Fryzek JP, et al. Mortality among aircraft manufacturing workers. *Occup Environ Med* 1999;56: 581–597.
26. Radican L, Wartenberg D, Rhoads GG, et al. A retrospective occupational cohort study of end-stage renal disease in aircraft

workers exposed to tri-chlorethylene and other hydrocarbons. *J Occup Environ Med* 2006;48:1–12.
27. Attia JR, D'Este C, Schofield PW, et al. Mental health in F-111 maintenance workers: the Study of Health Outcomes in Aircraft Maintenance Personnel (SHOHMP) general health and medical study. *J Occup Environ Med* 2006;48:662–691.
28. Iavicoli I, Carrelli G, Bergamaschi A. Exposure evaluation to airborne polycyclic aromatic hydrocarbons in an Italian airport. *J Occup Environ Med* 2006;48:815–822.
29. England EC, Carlton NG, Krevonick PL. The impact of ventilation systems on worker exposures during advanced composite material and fiberglass repair operations on military aircraft. *Appl Occup Environ Hyg* 2000;15:391–396.
30. Rest KM. Ethics and occupational health. In: Levy BS, Wegmon DW, eds. *Occupational health*, 2nd ed. Boston: Little, Brown and Company, 1988.
31. American College of Environmental Medicine. *Code of ethical conduct*. www.acome.org/OEML.inks, September 2006.
32. National Research Council, Committee on Air Quality in Passenger Cabins of Commercial Aircraft. *The airline cabin environment and the health of passengers and crew*. National Academy Press, 2002.
33. Lindgren T, Norback D, Andersson K, et al. Cabin environment and perception of cabin air quality among commercial aircrew. *Aviat Space Environ Med* 2000;71:774–782.
34. Rayman RB. Cabin air quality: an overview. *Aviat Space Environ Med* 2002;73:211–215.
35. Nagda NL, Koontz MD. Review of studies on flight attendant health and comfort in airliner cabins. *Aviat Space Environ Med* 2003;74:101–109.
36. Boeing Commercial Airplanes. *Commercial airplanes—cabin air systems*. 2006, available at http://www.boeing.com/commercial/cabinair/index.html, accessed January 2007.
37. Maresh CM, Armstrong LE, Kavouras SA, et al. Physiological and psychological effects associated with high carbon dioxide levels in healthy men. *Aviat Space Environ Med* 1997;68(1):41–45.
38. National Transportation and Safety Board. *NTSB Docket FTW98IA196: Determination of probable cause*. DC-8 mishap, available at http://www.ntsb.gov/ntsb/brief2.asp?ev_id=20001211X09850&ntsbno=FTW98IA196&akey=1, April 29, 1998.
39. Caldwell DC, Lewis RJ, Shaffstall RM, et al. *Sublimation rate of dry ice packaged in commonly used quantities by the air cargo industry*. Report DOT/FAA/AM-06/19. Federal Aviation Administration, 2006.
40. Melton CE. *Airline cabin ozone: an updated review*. Report DOT/FAA-AM-89/13. Federal Aviation Administration, 1989.
41. Spektor DM, Lippmann M, Thurston GD, et al. Effects of ambient ozone on respiratory function in healthy adults exercising outdoors. *Am Rev Respir Dis* 1988;136(4):821–828.
42. Higgins EA, Letegola MT, McKenzin JM, et al. *Effects of ozone on exercising and sedentary adult men and women representative of the flight attendant population*. Report No. FAA-AM-79-20. Federal Aviation Administration, 1979.
43. Higgins EA, Letegola MT, Melton CE, et al. *Effects of ozone (0.30 ppm) on sedentary men representative of airline passengers and cockpit crewmembers*. Report No. FAA-AM-80-9. Federal Aviation Administration, 1980.
44. Spengler JD, Ludwig S. Ozone exposures during trans-continental and trans-pacific flights. *Indoor Air* 2004;14(Suppl):67–73.
45. Luna LK, Panning S, Grywna K, et al Spectrum of viruses and atypical bacteria in intercontinental air travelers with symptoms of acute respiratory infection. *J Infect Dis* 2007;195:675–679.
46. Mangili A, Gendreau MA. Transmission of infectious diseases during commercial air travel. *Lancet* 2005;365:989–995.
47. World Health Organization. *Tuberculosis and air travel: guidelines for prevention and control*, 2nd ed, 2006.
48. CDC. Exposure of passengers and flight crew to *Mycobacterium tuberculosis* on commercial aircraft, 1992–1995. *MMWR Morb Mortal Wkly Rep* 1995;44:137–140.
49. Moser MR, Bender TR, Margolis HS, et al. An outbreak of influenza aboard a commercial airliner. *Am J Epidemiol* 1979;110:1–6.
50. Brownstein JS, Wolfe CJ, Mandl KD. Empirical evidence for the effect of airline travel on inter-regional influenza spread in the United States. *PLoS* 2006;3(10):1826–1835.
51. Olsen SJ, Chang HL, Cheung TY, et al. Transmission of the severe acute respiratory syndrome on aircraft. *N Engl J Med* 2003;349:2416–2422.
52. Vogt TM, Guerra MA, Flagg EW, et al. Risk of severe acute respiratory syndrome-associated coronavirus transmission aboard commercial aircraft. *J Travel Med* 2006;13:268–272.
53. Public Broadcasting System. *NOVA Archives, The most dangerous woman in America, the history of quarantine*. http://www.pbs.org/wgbh/nova/typhoid/, accessed March 2007.
54. World Health Organization. *Revision of the International Health Regulations*. available online at http://www.who.int/csr/ihr/IHRWHA583_en.pdf, accessed February 2007.
55. Baker MG, Fidler DP. Global public health surveillance under new international health regulations. *Emerg Infect Dis* 2006;12(7).
56. Eisenberg MS, Garrslev K, Brown W, et al. Staphylococcal food poisoning aboard a commercial aircraft. *Lancet* 1975;2(7935):595–599.
57. Tauxe RV, Tormey MP, Mascola L, et al. Salmonellosis outbreak on transatlantic flights; foodborne illness on aircraft: 1947–1984. *Am J Epidemiol* 1987;125(1):150–157.
58. Hedberg CW, Levine WC, White KE, et al. An international foodborne outbreak of shigellosis associated with a commercial airline. *JAMA* 1992;268:3208–3212.
59. CDC. Cholera associated with an international airline flight, 1992. *MMWR Morb Mortal Wkly Rep* 1992;41:134–135.
60. CDC. Update cholera—western hemisphere, 1992. *MMWR Morb Mortal Wkly Rep* 1992;41:667–668.
61. World Health Organization. *Report of the informal consultation on aircraft disinsection*. Report WHO/PCS/95.51. Geneva: WHO, Nov. 610, 1995.
62. Kozarsky P, Arguin P, Navin A. *Conveyance and transportation issues: air travel, including disinsection*. In: *Travelers' health: yellow book, health information for international travel*, Centers for Disease Control and Prevention. Mosby, 2005–2006.
63. Gratz NG, Steffen R, Cocksedge W. Why aircraft disinsection? *Bull World Health Organ* 2000; 78(8).
64. Das R, Cone J, Sutton P. Aircraft disinsection. *Bull World Health Organ* 2001;79(9):900–901.
65. Kilburn KH. Effects of onboard insecticide use on airline flight attendants. *Arch Environ Health* 2004;59(6):284–291.
66. Rayman RB. Aircraft disinsection. *Aviat Space Environ Med* 2006;77:733–736.
67. Airport malaria in Luxembourg. Case report by Robert H. *Euro Surveill* 19 August 1999;3(34):1.
68. Conlin C, Berendt AR, et al. Runway malaria. *Lancet* 1990; 335(8687):472–473.
69. Intergovernmental Panel for Climate Change. *Special report: aviation and the global atmosphere*. Geneva, Switzerland: IPCC, 1999.
70. US Environmental Protection Agency. *Regulatory announcement: new emission standards for new commercial aircraft engines*. EPA420-F-05-015, available at http://www.epa.gov/oms/regs/nonroad/aviation/420f05015.htm, 2007.
71. Federal Aviation Administration. *Aviation and emissions—a primer*, 2005. Available at http://www.faa.gov/regulations_policies/policy_guidance/envir_policy/media/AEPRIMER.pdf, accessed February 2007.
72. Stolarski RS, Krueger AJ, Schoeberl MR, et al. Nimbus 7 satellite measurements of the springtime antarctic ozone decrease. *Nature* 1986;322:808–811.
73. Air Transport Association of America. *ATA Issue Brief: US Airlines support development of alternative fuels*. http://www.airlines.org/government/issuebriefs/Alt+Fuels.htm, October 2006.

74. Clark C, Martin R, van Kempen E, et al. Exposure-effect relations between aircraft and road traffic noise exposure at school and reading comprehension. *Am J Epidemiol* 2006;163:27–37.
75. O'Brien K, Friedberg W, Sauer, HH, et al. Atmospheric cosmic rays and solar energetic particles at aircraft altitudes. *Environ Int* 1996;22(Suppl 1):S9–S44.
76. Boice JD, Blettner M, Auvinen A. Epidemiologic studies of pilots and aircrew. *Health Phys* 2000;79(5):576–584.
77. Rafnsson V, Hrafnkelsson J, Hrafnkelsson J. Incidence of cancer among commercial airline pilots. *Occup Environ Med* 2000;57:175–179.
78. Rafnsson V, Hrafnkelsson J, Tulinius H, et al. Risk factors for cutaneous malignant melanoma among aircrews and a random sample of the population. *Occup Environ Med* 2003;60:815–820.
79. Linnersjö A, Hammar N, Dammstrom BG, et al. Cancer incidence in airline cabin crew: experience from Sweden. *Occup Environ Med* 2003;60:810–814.
80. Gundestrup M, Storm JJ. Radiation-induced acute myeloid leukemia and other cancers in commercial jet cockpit crew: a population-based cohort study. *Lancet* 1999;354:2029–2031.
81. Zeeb H, Blettner M, Langner I, et al. Mortality from cancer and other causes among airline cabin attendants in Europe: a collaborative cohort study in eight countries. *Am J Epidemiol* 2003;158(1):35–46.
82. Tokumaru O, Haruki K, Bascal K, et al. Incidence of cancer among female flight attendants: a meta-analysis. *J Travel Med* 2006;13(3):127–132.
83. Stewart T, Stewart N. Breast cancer in female flight attendants. *Lancet* 1995;346:1379.
84. Health Physics Society. Report on screening with backscatter x-ray machines. Home page http://hps.org, http://hps.org/hpspublications/articles/screenindx-ray.html, accessed March 2007.
85. Miniss P, Young DF, Garber DP, et al. Transformation of contrails into cirrus during SUCCESS. *Geophys Res Lett* SUCCESS Special Issue, October 1997;25(8):1157–1160.
86. Travis DJ, Carleton AM, Lauritsen RG. Contrails reduce daily temperature range. *Nature* 2002;418:601.
87. Federal Aviation Administration. Order 7110.65R, *Air traffic control*, Chapter 9, section 4. Fuel Dumping, February 16, 2006.
88. Federal Aviation Administration. *Aeronautical information manual*. Chapter 6, section 6-3-5. Fuel Dumping, August 3rd, 2006.
89. Good RE, Clewell HJ. Drop formation and evaporation of JP-4 fuel jettisoned from aircraft. *J Aircr* 17(7):450–456.
90. Clewell H. *Evaporation and groundfall of JP-4 jet fuel jettisoned by USAF aircraft*. Final Technical Report ESL-TR-80-56. Engineering and Services Laboratory, Air Force Engineering and Services Center, 1980.

RECOMMENDED READINGS

American College of Occupational and Environmental Medicine. *Occupational medicine practice guidelines*, 2nd ed. ACOEM, 2004.

American Medical Association. *Guides to the evaluation of permanent impairment*, 5th ed. AMA, 2001.

Aerospace Medical Association. *Medical guidelines task force, medical guidelines for airline travel*, 2nd ed. 2003. *Aviat Space Environ Med* 2003;74(5): Section II, A1– A6.

Aerospace Medical Association. Emerging infectious diseases including severe acute respiratory syndrome: guidelines for commercial air travel and air medical transport. *Aviat Space Environ Med* 2004; 75:85–86.

Friedberg W, Copeland K, Duke FE, et al. Radiation exposure of aircrews. *Occup Med* 2002;17(2):293–309.

Green, KB, ed. The Aviation Industry. State of the art review. *Occup Med* 2002;17.

Levy B, ed. *Occupational and environmental health*, 5th ed. 2006.

Penner JE, Lister DH, Griggs DJ, et al. *Intergovernmental panel on climate change special report: aviation and the global atmosphere*. 1999.

Ribak, J, ed. *Occupational health in aviation*. Academic Press, 1995.

Rom, W, ed. *Environmental and occupational medicine*, 4th ed. 2007.

Rosenstock L, Cullen MR, Brodkin CA, eds. *Clinical occupational and environmental medicine*, 2nd ed, Elsevier Saunders, 2005.

Sohail MR, Fisher PR. Health risks to air travelers. *Infect Dis Clin North Am* 2005;19:67–84.

Thibeault, C. Airliner cabin air quality. *Occup Med* 2002;17(2):279–292.

American Conference of Governmental Industrial Hygienists. *Threshold limit values for chemical substances and physical agents*.

SUGGESTED WEB SITES

Agency for Toxic Substances and Disease Registry (ATSDR). www.atsdr.cdc.gov.

American Association of Occupational Health Nurses. www.aaohn.org.

American Board of Preventive Medicine. www.abprevmed.org.

American College of Occupational and Environmental Medicine. http://www.acome.org.

American College of Occupational Safety and Health. www.ACOSH.org.

American Conference of Governmental Industrial Hygienist. www.acgih.org.

Centers for Disease Control and Prevention. http://www.cdc.gov/travel/.

Department of Labor. www.dol.gov.

Department of Transportation. www.dot.gov.

Environmental Protection Agency. www.epa.gov.

Federal Aviation Administration, http://jag.cami.jccbi.gov./cariprofile.asp.

Health Physics Society. http://hps.org.

International Civil Aviation Organization. www.icao.int/.

Intergovernmental Panel on Climate Change. http://www.ipcc.ch/.

National Council on Radiation Protection and Measurements (NCRP). http://www.ncrponline.org/.

National Institute for Occupational Health and Safety. www.cdc/niosh/homepage/.

Occupational Safety and Health Administration. www.osha.gov.

Total Ozone Mapping Spectrometer. http://jwocky.gsfc.nasa.gov/.

World Health Organization's International Health Regulations. http://www.who.int/csr/ihr/ihr1969.pdf.

World Health Organization's IHR 2005. Revision. http://www.who.int/csr/ihr/IHRWHA583_en.pdf.

CHAPTER 22

Women's Health Issues in Aerospace Medicine

Monica B. Gorbandt and Richard A. Knittig

> My ambition is to have this wonderful gift produce practical results for the future of commercial flying and for the women who may want to fly tomorrow's planes.
>
> —*Amelia Earhart*

This chapter is primarily concerned with the current state of women's health as related to aerospace medicine. Although much has been conjectured and written about the training and working of women in the aerospace environment, this chapter addresses the evidence provided in the current state of the literature. Women have made and are making significant contributions across the aerospace spectrum from commercial to military to space flight. As women meet these challenges, the flight surgeon must be aware of issues unique and pertinent to women's overall health and well-being. Except for possibly the latter stages of pregnancy, women have no restrictions or significant limitations in flight performance. The health care professional can be confident about addressing particular women's health issues as noted in this chapter in standard manner resulting in sustained high performance by women in all aspects of flight or for women participating only as passengers.

Women's involvement in aviation begins with its earliest days that continues currently both in air and space travel. Currently in the United States, women comprise 6% of all Federal Aviation Administration (FAA) pilots with number totaling 36,584 (1). Within the United States military, women make up roughly 6% of all fixed and rotary wing pilots (1). Thirty-two percent of National Aeronautics and Space Administration (NASA) employees are women with approximately 18% serving in scientific or engineering roles. Of the 91 current active astronauts, 18% or 20% are women and of the 15 international astronauts, 2 are women (2). Reviewing FAA data, the number of women in all classes decreased over the last 25 years but this is offset by the remarkable 13-fold increase in the first (air transport pilot) and second class (commercial) female pilot population. Women are represented in all aviation support roles from mechanic to flight engineer, but only constitute a majority in the flight attendant category at 80% (1).

Contributions or firsts for women occurred in every decade since the start of powered flight in 1903 by the Wright brothers and continues through today. The following is a brief overview of the few notable contributions and achievements by women in the aerospace field.

1910—Raymond De Laroche of France is the first woman in the world to receive a pilot license.

1911—Harriet Quimby is the first American woman to earn a pilot certification and fly across the English Channel.

1921—Bessie Coleman is the first African American, man or woman, to receive a pilot license.

1932—Amelia Earhart of the United States is the first woman to cross the Atlantic Ocean solo in an aircraft.

1934—Helen Richey, an American, is the first woman hired as a pilot for a United States Commercial Airline.

1942—Mary Van Segue of the United States is certified as the first female Air Traffic Controller.

1942—The United States Women's Air Force Service Pilots (WASPs) led by Jackie Cochran are the first American women to pilot U.S. military aircraft.

1953—Jacqueline Cochran is the first woman to break the sound barrier done in a Boeing North American F86 Sabre jet.

1963—Valentina Tereshkova of the United Soviet Socialist Republic is a cosmonaut and the first woman in space aboard the Vostok 6.

1973—Emily Warne, an American, is hired as the first female air transport pilot for a modern, jet-equipped scheduled airline, Frontier Airlines.

FIGURE 22-1 Portrait of Sally Ride, first American woman in space as part of the STS 7 shuttle mission. Courtesy of NASA.

1974—Barbara Raines becomes the first woman pilot for the U.S. military.

1983—Sally Ride is the first American woman in space as part of the STS 7 shuttle mission (Figure 22-1).

1986—Jenna Yeager copilots the Voyager credited with the first around the world, nonstop, nonrefueled flight.

1993—U.S. Department of Defense, through Secretary of Defense, Les Aspin, opens combat aviation to women.

1999—Lt. Col. Eileen Collins of the United States Air Force (USAF) is the first woman to serve as a space shuttle commander. She previously piloted two Space Transportation System (STS) missions (Figure 22-2).

2007—Astronaut Sunita Williams aboard the International Space Station set a record for the number of space walks and total time in space walks for a woman at four walks totaling 29 hours 17 minutes.

FIGURE 22-2 Lt. Col. Eileen Collins of the United States Air Force, the first woman to serve as a space shuttle commander. Courtesy of NASA.

PREGNANCY IN AVIATION

Policy

Standardized policies regarding routine national and international commercial travel of pregnant passengers are nonexistent (3). Civil air company policies, however, do take into account the length of the pregnancy. The more advanced the gestation, the more likely rupture of membranes, labor, or delivery will occur. Predictors for many pregnancy-related events are not always readily evident. Fifty percent of the pregnancies that result in preterm delivery have no identifiable risk factors (4). What are the implications? Diversion for even a commuter flight can be expected to take 30 to 45 minutes depending on meteorologic conditions and air traffic. Responding commercial airlines in a survey by Breahtnach et al. reported that only 70% trained aircrew in delivery and fewer than 30% had a full delivery kit (3). Therefore, a conservative approach with some flexibility is generally employed. Many airline medical departments allow pregnant travelers to fly at their discretion to 36 weeks estimated gestational age for domestic flights and 35 weeks for international, or specifically, transcontinental or transoceanic flights (5). Exceeding airline restrictions generally requires a medical provider statement verifying that labor is not imminent and no underlying complications exist.

Women with complicated pregnancies may encounter other risks with air travel. Absolute contraindications to air travel include ruptured membranes, bleeding during pregnancy, diagnosed ectopic pregnancy, and severe preeclampsia. First trimester bleeding can represent an undiagnosed ectopic pregnancy or threatened/incomplete abortion. Fifteen to 20% of clinically recognized pregnancies end in spontaneous abortion. Second and third trimester bleeding can represent labor, incompetent cervix, abruption, or placenta previa (6). Pregnancies complicated by multiple gestations, a history of preterm labor (PTL), or existing uterine irritability are predisposed to early delivery. Severe anemia affects oxygen delivery to the placenta and should be corrected before flight or minimally necessitates in-flight oxygen supplementation. Oxygen therapy should also be supplied for conditions that potentially compromise placental reserve such as intrauterine growth restriction, postmaturity, and preeclampsia.

The risk with air travel in pregnancy may be minimal in comparison to the environmental risk, such as endemic malaria, that may be encountered in the ultimate destination. The best policy is to consider all aspects of the proposed journey including lodging, activities, food, and medical support, and to mitigate risk that each of these elements poses by establishing sound prenatal care. Pretravel prenatal care typically includes ultrasonography, assessment of immune status to various infections, the need for immunization, malaria prophylaxis, and creation of a prenatal record. Ultrasonography facilitates more precise dating of the pregnancy and helps confirm suspected multifetal gestation and ectopic pregnancy. Non contraindicated immunizations can be administered. Typically, live viral vaccinations such as mumps, rubella, oral polio, varicella, and yellow fever are avoided in pregnancy. Prescriptive medications, including malaria chemoprophylaxis and other stand-by therapies such as antiemetics and antidiarrheals should be considered (7). The prenatal record should be carried together with the passport, visa, and immunization records.

Pregnant aircrew have distinct responsibilities and required activities in the performance of their flight duties. The changing balance, flexibility, mobility, and body habitus in pregnancy become evident in the second trimester and may interfere with the ability to safely pilot or assist passengers during an emergent egress. Therefore, commercial aircrew is generally restricted from duties after 28 weeks or completion of the second trimester (8). Although pregnancy is not disqualifying in general aviation, the aircrew must be made aware of the impact flying has on the third trimester such as cockpit ergonomics and placental reserve. Placental maturation continues throughout pregnancy. Maturation beyond 34 to 36 weeks is affiliated with several processes including microcalcification deposition that affect oxygen delivery to the fetus and ultimately lower fetal respiratory reserve. This lowered reserve may not pose a problem in the uncomplicated pregnancy in an oxygen tension encountered at 8,000 ft (the commercial cabin), but may become problematic for the nonacclimated fetus in an oxygen tension encountered at 14,000 ft (general aviation, nonpressurized cabin).

Women who fly high-performance military aircraft or are engaged in aerial aerobatics will experience high levels of accelerative force (G force). Egress through an ejection seat will result in higher accelerative force. These forces can be sudden, unexpected, and violent and may pose an unacceptable maternal or fetal risk in the gravid aviator. Resultant outcomes would be dependent on gestational age. Significant first trimester insults are likely limited to a fetal loss with no immediate bleeding and would not result in any additional maternal morbidity beyond the nongravid female. Therefore, the gravid female aviator would be just as successful piloting the aircraft or surviving the egress. Significant second or third trimester exposure poses the additional risk of uterine rupture. Twenty percent of cardiac output flows to the uterus by 30 weeks. Therefore, rupture of the uterus or placental abruption would likely result in both fetal loss and profound maternal morbidity or mortality. In this scenario, it is unlikely that she would be able to pilot the aircraft (aircraft loss) or survive the ejection. There are no available studies that address these issues, and pregnant aviators should seek counsel from both their obstetrician and their flight surgeon to determine the point in the pregnancy where temporary grounding would be appropriate. Informed consent must be universally applied to performance aircraft or platforms with ejection seats.

Physiology Impacts in Flight

The unique physiology of pregnancy is impacted by the flight environment (Table 22-1). In general, these considerations apply to the gravid aircrew/frequent flyer or the infrequent traveler. Aeromedical providers must have familiarity with system-specific maternal physiologic changes of pregnancy as well as fetal physiology in order to perform appropriate consultation and policy promulgation for the gravid female or provide aeromedical evacuation (AE) *en route* care for the pregnant (or newly postpartum) patient. As an example, an asymptomatic 31-year-old passenger at 30 weeks gestation with focal findings of a systolic ejection murmur with an S_3 gallop and lower dependent edema is likely normal and cleared to schedule her commuter flight as opposed to same findings and suspicion of heart failure in a nongravid female of the same age.

Fetal

Monitoring of maternal and fetal physiologic reactions during commercial flights demonstrate moderate, but significant maternal cardiopulmonary changes, including a transcutaneous PO_2 drop of 25% at maximum cabin altitude (7,855 ft), but no concomitant fetal tachycardia, bradycardia, or loss of variability (9). Therefore, this cabin altitude, corresponding to a maternal PaO_2 of 64 mm Hg and an oxygen saturation of 90%, introduces a maternal hypoxia that does not appear to acutely affect the normal fetus. For periods up to 30 minutes, animal models have demonstrated that during a sudden decompression at 15,000 ft, maternal arterial PO_2 drops to 46 mm Hg (O_2 saturation 82%) without any suspected fetal hypoxic degeneration of the brain or heart. This relative fetal tolerance to hypoxia exists because the fetal oxygen supply to critical organs is maintained through a combination of physiologic advantages of the fetal circulation and fetal compensatory mechanisms such as redistribution of blood flow to vital organs (shunting) and decreased oxygen consumption (10).

There are three physiologic advantages of the fetal circulation in matters of oxygen-carrying capacity and dissociation. First, the fetal circulation carries more hemoglobin (gm/dL) than the adult. Second, the fetal hemoglobin (HbF) oxygen dissociation curve is shifted to the left of adult hemoglobin (HbA), and thereby allows 20% to 30% increased oxygen-carrying capacity in the fetus. Lastly, the Bohr effect has a positive influence on gaseous oxygen transfer on the hemochorial circulation. Fetal blood, derived from the umbilical blood flow, enters the fetal placenta carrying large amounts of carbon dioxide that rapidly diffuses into the intervillous spaces of the maternal placenta. Local loss of carbon dioxide makes the fetal blood more alkaline and shifts the oxygen dissociation curve left and upward. The opposite occurs with maternal carbon dioxide gain. As a result, the oxygen-binding capacity of fetal blood is raised while maternal blood is lowered, thereby allowing for enhanced oxygen transfer. The Bohr effect operates in one direction for maternal blood and in the other for fetal blood (11).

Maternal

The air travel impacts on the gastrointestinal physiologic changes of pregnancy are occasionally manifested by abdominal pain and nausea/vomiting. Intestinal gas expansion, occurring at altitude, can cause bloating and

TABLE 22-1

[a]The Potential Maternal Aeromedical Impacts of the Flight Environment on the Gravid Female

Organ System	*Physiologic Change of Pregnancy*	*Flight Environmental Threat*	*Potential Maternal Aeromedical Impact (s)*
Cardiovascular	Decreased systemic vascular resistance and increased venous capacitance	Prolonged immobility	Vasovagal response, syncope
Respiratory	Increased tidal volume, decreased total lung capacity, and decreased residual volume yielding physiologic dyspnea of pregnancy	Decreased cabin P_{AO_2}	Worsening dyspnea
Hematologic	Increased plasma volume yielding nasopharyngeal edema (compounded by nasopharyngeal hyperplasia)	Ambient pressure changes	Barosinusitis, baro-otitis, syncope
	Increased clotting factors and fibrinogen, uterine compression of the vena cava (venous stasis)	Prolonged immobility	Thromboembolic phenomenon
Gastrointestinal	Delayed gastric emptying, nausea vomiting of pregnancy	Motion (air sickness)	Nausea/vomiting
	Slowed GI motility, mild distension	Ambient pressure changes	Abdominal distension, colic
Musculoskeletal	Altered lumbar curvature, gravid uterine impingement, joint laxity	Prolonged immobility, aircraft vibration, poor cockpit ergonomics	Low back pain, pelvic pain
	Changing center of gravity	Turbulence	Altered balance and increasing risk of traumatic fall

[a]See also Chapter 8.

colicky abdominal discomfort or pain that is compounded by abdominal crowding from the pregnancy. Therefore, gas-producing foods should be avoided a few days before the flight. Nausea of early pregnancy may be compounded by air travel. Therefore, physicians should consider prescribing antiemetics for these women (8).

The enlarging, gravid uterus alters the center of gravity and lends to a more unsteady gait. Loss of balance and lack of coordination increases the risk of falls. Ligamentous laxity and vascular engorgement increase the risk of injury. Third-trimester abdominal trauma may cause a placental abruption. Because air turbulence cannot always be predicted, the seat belt should be worn at all times when seated. The belt should be fastened low near the pubic symphysis or on the upper thighs in order to reduce the potential injury to abdominal contents. Cabin ambulation in the third trimester should be done with caution (8).

Most data confer a weak association between air travel and venous thromboembolic phenomenon (12). Pregnancy-altered clotting factors, thrombophlebitis, and dependent venous stasis, attributed to volume expansion and obstruction of the vena cava from uterine compression, increase the risk of thromboembolic phenomenon in flight. These pregnancy-related changes begin late first trimester and persist to 6 weeks postpartum. This risk may be potentiated by being immobile in cramped seats for long periods of time. Loose-fitting clothing should accompany periodic leg stretching and hourly ambulation (when possible) in flight. Gravid women with a prior thromboembolic event or additional factors that predispose them to venous thrombosis should consult their physician regarding anticoagulation with low molecular weight heparin. The efficacy of acetylsalicylic acid in preventing deep vein thrombosis (DVT) is conflicting (5). Support stockings, frequent movement, loose clothing, and adequate hydration may diminish DVT risk (6).

Aeromedical Evacuation of the Obstetric Patient

Perinatal regionalization, emphasized strongly beginning in the 1990s, has been associated with improved outcome for very low birth weight infants and for women with complications requiring intensive services. This phenomenon involves stabilization of the mother, intrauterine transfer, and the optimum delivery at a medical center that has the volume to sustain costly technology and specialized personnel (13). Generally, the best and most efficient fetal transport mechanism, delivering oxygen and nutrition to the fetus, remains the gravid mother. Clinical circumstances may dictate it is safer to transport medical personnel to the patient than transport an unstable patient in an unstable environment. General contraindications to maternal air transport include maternal instability, a rapidly deteriorating fetus, imminent delivery, lack of experienced (*en route*) medical attendants, and hazardous flight conditions (meteorologic). This assessment of transport versus local care is best left to the accepting or aeromedically validating perinatal team. As with all medical evacuation, arrangements for transfer should be made before the transport. Standing agreements with referral hospitals should be established to provide sufficient guidance for transport and provide communication consistency (14).

The transport team should be familiar with the aviation environment and skilled in perinatal care that includes the ability to perform a vaginal delivery. When possible, the evacuating platform should be suited to support equipment that may be needed during transport. Standard equipment includes a delivery kit, uterotonics, oxygen, intravenous fluids, an infant warmer, and maternal and fetal stabilization equipment. Pharmacologic agents such as tocolytics, oxytocin, calcium gluconate (magnesium toxicity), antihypertensives, and antiemetics are useful while handling the more common complications during transport (Table 22-2). Preflight assessment and preparation typically include a cervical check [except in suspected placenta previa or preterm premature rupture of membranes (PPROM) without labor] and intravenous access and adequate airway, if indicated. Transport in a left lateral recumbent position displaces the gravid uterus off the vena cava and thereby increases maternal venous return and subsequent cardiac output and uterine perfusion. Advanced cardiac life support considerations are the same as for the nongravid female. The fetal heart rate can be assessed with a handheld Doppler with digital display (14). Oxygen supplementation should be used liberally as it improves fetal cerebral cortical oxygen tension (15). Planning the AE, including the decision to use fixed wing or rotary aircraft, depends on a myriad of factors including available assets, meteorologic conditions, geography/terrain, airfield support, landing areas, and the distance to the nearest appropriate medical facility (14).

TABLE 22-2

Diagnosis and In-flight Complications of Aeromedevac Transport of Obstetric Patients

Diagnosis (in %)		*Complications (in %)*	
Preterm labor (PTL)	33.0	Nausea/vomiting	15.0
Preterm premature rupture of membranes (PPROM)	21.3	Increased contractions	7.0
Pregnancy-induced hypertension	21.3	Other[a]	3.0
PTL and PPROM	7.5		
Other	8.8		

[a]Other included hypertension, hypotension, and decreased maternal respiratory drive. (From O'Brien DJ, Hooker EA, Hignite J, et al. Long-distance fixed wing transport of obstetrical patients. *South Med J* 2004;9:816–818.)

Most AE transports will occur for fetal purposes and fall in three categories or a combination of PTL, PPROM, and pregnancy-induced hypertension(PIH)/preeclampsia (Table 22-2).

In patients who present with PTL or PPROM, tocolytic therapy is frequently employed before or during air transport. The goal of this therapy is to prevent in-flight delivery and allow time for administration of corticosteroids (promote fetal lung maturity) and group B streptococcus prophylaxis (prevent meningitis and other potential infections). These three measures have been shown to reduce perinatal morbidity and mortality attributed to prematurity (4).

Severe maternal hypertension or PIH can be complicated by pulmonary edema, eclampsia, and fetal compromise. *En route* care for eclampsia includes blood pressure control, maternal seizure control and suppression, injury prevention, oxygenation, and minimizing the risk of aspiration. Use of magnesium for seizure control must be closely monitored because it can diminish the maternal respiratory drive in high doses and cause apnea (14).

Outcomes

The preponderance of existing evidence, albeit limited, indicates that the commercial aircraft is not deleterious to pregnancy. This sentiment is shared by 93% of obstetricians in the United Kingdom (16). As discussed, the oxygen levels at normal operating altitudes in pressurized aircraft are adequate for the normal fetus in flight. Pregnancy outcomes for chronic exposure to altitude by way of the aircraft do not significantly deviate from the norm (17,18). Similarly, data examining spontaneous pregnancy loss in flight attendants indicates that there is no difference in miscarriage rate from the general population (19,20).

COSMIC RADIATION AND IMPACT ON PREGNANCY AND FEMALE HEALTH

Except for the occasional solar particle event, cosmic radiation exposures for the infrequent traveler are minimal and are unlikely to influence pregnancy outcomes such as spontaneous abortion, growth restriction, congenital malformations, mental retardation, and childhood malignancy induction (21). However, exposure for the frequent gravid traveler or aircrew must be weighed, and in certain cases, controlled. Cumulative fetal exposure less than 20 mSv should not result in harm (22). It is prudent to apply a buffer to this value. Therefore, organizations and/or medical providers should communicate risk and implement administrative controls such as modifying work schedules or choosing alternative means of transportation in order to ensure that the cumulative conceptus dose does not exceed 1 mSv (International Commission on Radiological Protection) (23). Depending on the controlling regulatory body, risk communication and control implementation may be either advisable or regulatory in nature (21) (see also Chapter 8).

Several studies have looked for an excess of radiation-induced cancer, specifically melanoma and breast, in female aircrew. A recent meta-analysis has indicated a slight, significant excess of breast cancer incidence reflected in the cumulative relative risk (RRc) of 1.41 (1.22–1.62) ($p < 0.0001$) and of malignant melanoma RRc 2.13 (1.58–2.88) ($p < 0.0001$) in female flight attendants, but no significant excess of cancer incidence when considering all types (24). However, attributing causation to the effects of ionizing radiation is difficult because a myriad of other exposures such as second-hand smoke, reproductive factors, organic pesticides applied in aircraft, delayed childbearing, differential breast feeding rates, and lifestyle may act as confounders or covariates (see also Chapter 8).

GYNECOLOGIC ISSUES AND FLIGHT IMPACT

Gynecologic disorders rarely cause sudden incapacitation in flight. Treatment efficacy should index onset and duration of pain relief pertinent symptoms, and functionality outcomes including qualitative work performance and absenteeism. Medications with significant side effects (especially central nervous system) should not be used during performance of aviation duties. A period of temporary grounding may be appropriate when new medications are initiated.

Dysmenorrhea

Dysmenorrhea is pain with menstruation and can be separated into primary and secondary forms. Primary dysmenorrhea, prevalent in 40% to 50% of young women and accounting for 15% of missed workdays in this cohort, is affiliated with the ovulatory cycle and generally occurs in the absence of other gynecologic pathology; whereas, secondary dysmenorrhea often occurs in the presence of gynecologic conditions such as endometriosis, adenomyosis, uterine leiomyomata, pelvic inflammatory disease, and cervical stenosis. Dysmenorrhea is characterized as spasmodic pelvic cramps beginning shortly before menses and lasting 2 to 3 days. It is usually a time-predictable and time-limited condition that can be factored in flight planning. It may be accompanied by lower back pain, vomiting, headache, dizziness, and diarrhea that can be distracting in flight.

Management of dysmenorrhea is supportive, pharmacologic, and/or surgical. Empiric medicines will satisfactorily relieve pain in 80% to 90% of women (25). Nonmedical responders, deemed after 3 to 6 months of treatment failure, will generally undergo imaging and/or laparoscopy for evaluation of secondary etiologies.

Premenstrual Syndrome

Premenstrual symptoms affect 85% of menstruating women. Severe symptoms occur in 5% to 10% of women and can cause impairment. Although serotonergic dysregulation is currently the most plausible etiology, the exact etiology of premenstrual syndrome (PMS) is not completely understood (26). Recent, stricter criteria for the diagnosis of PMS have been established by the American Psychiatric Association (APA) and comprise the following essential elements (27):

1. Affective and somatic symptoms of PMS
2. Symptoms relegated to the luteal phase
3. Impairment of daily functioning
4. Absence of other maladies that could account for the symptoms

Affective symptoms such as depression, irritability, anxiety, confusion, and somatic symptoms such as headache, bloating, and breast tenderness can decrease concentration and cause inattention, indecisiveness, and fatigue, all of which are incompatible with aviation duties. The diagnosis should be established by a prospective diary of symptoms correlated with the menstrual cycle and fulfilling the APA elements. A symptom-free interval must exist. Long-standing therapies including oral contraceptive pills (OCPs), aerobic exercise, supportive counseling, and dietary modification have demonstrated varying success and should be tailored to the individual patient's symptoms. Recently, selective serotonin reuptake inhibitors have been shown to be effective (26).

Abnormal Gynecologic Bleeding

Abnormal gynecologic bleeding (nonpregnant) may be anovulatory or ovulatory in women of the reproductive years. Should anemia occur, it may cause fatigue manifested by decreased performance, compromise adaptation at lower oxygen tensions, and reduce G tolerance. Abnormal uterine bleeding in the menopausal woman that occurs in the absence of hormone replacement therapy is clinically concerning and warrants a thorough evaluation for malignancy.

Anovulatory bleeding is common at the extremes of reproductive age and results from a lack of consistent ovulation and progesterone production that cause maturation of the endometrium. Conception failure results in progesterone withdrawal and a time predictable menses. Other causes of anovulatory bleeding include thyroid disease, obesity, stress, exercise, polycystic ovarian syndrome, and weight loss. Anovulatory bleeding generally responds to contraceptive (OCP) suppression, cyclic progestin treatment, or clinical improvement of identified medical conditions.

Ovulatory bleeding is usually caused by structural abnormalities including leiomyomata, adenomyosis, endometrial/cervical polyps, and malignancy or medical conditions such as gynecologic infection or blood dyscrasia. Infections are diagnosed by physical examination or endometrial aspirate and treated with antimicrobials. Typically, structural lesions are identified by a combination of imaging and surgical diagnostics, including ultrasonography, saline infusion sonography, and hysteroscopy. As with anovulatory bleeding, most structural lesions, except malignancy, polyps, and submucous fibroids, may be given a trial of 3 to 6 months of medical therapy. Medical nonresponders are generally treated surgically (28).

Endometriosis

Endometriosis is a pervasive, symptomatically complex disease of reproductive ages that may be defined as the presence of endometrial gland-like tissue and stroma at an extrauterine site and can range from subclinical foci (found on incidental laparoscopy) to severe infiltrating diseases involving the bowel, bladder, and ureters. A rare association with spontaneous pneumothorax exists (29). Endometriosis occurs in 15% of asymptomatic women presenting for laparoscopic surgery for tubal ligation, 40% of women with chronic pelvic pain, and 60% of women with dysmenorrhea, 5% to 50% of women with infertility problems, and 20% of women hospitalized for pelvic pain (30). The definitive pathophysiology of the disease process remains uncertain; however, the direct surgical visualization confirmed by histologic examination remains the gold standard for diagnosis. Symptom presentation varies and can include dysmenorrhea, pelvic pain, and low back pain that can be distracting in flight.

Diverse opinions exist regarding the optimal therapy for endometriosis. Most strategies involve an initial trial of ovarian suppression and symptom amelioration with OCP followed by gonadotropin-releasing hormone (GnRH) agonists for OCP failures. GnRH agonists can lead to menopausal symptoms including hot flashes and mood alterations and may affect flight certification. Low-dose estrogen add-back can be used, if needed. If no clinical improvement ensues, then surgical treatment is generally performed or the diagnosis reconsidered (31).

IMPACT OF ANTHROPOMETRICS ACCOMMODATION AND BIOMECHANICS FOR WOMEN IN AIRCRAFT

In general, the key to aircraft operation is strength measure rather than cockpit fit. Lower body strength between men and women is comparable, but experimentally differences exist in upper body strength. This distinction may blur in the current modern fixed and rotary wing aircraft where stick and rudder control are of lesser importance for piloting. Most studies looking at these differences focused on these stick and rudder skills in older airframes. A critical element of these studies was handling hydraulic failure that arguably in the present day aircraft is no longer a factor in control. From a size perspective, the 50th percentile female correlates to the 5th percentile male. Challenges in cockpit fit and access to controls as well as suitable fit of personal protective equipment exist. Women on average are shorter and weigh less than men. The average female height in America is 64 inches. In addition, women have a shorter arm length compared to men of the same height. All of these parameters can affect cockpit fit and potentially aircrew performance.

Schender et al. conducted a series of small subject number studies looking at the small stature female, defined as a female at the 5th U.S. percentile weighing 120 lb or less (32). They assessed dynamic strength capabilities of these subjects in the performance of flight profile tasks, the ability to successfully eject, and the capability to support helmets with added devices under acceleration stresses (32,33). Operational flight simulations for aerial combat maneuvers, emergency procedures, and standard fighter flight were used to evaluate upper body muscle endurance. Although with only a small number of subjects, the authors concluded that women of small stature had strength comparable to men in dynamic activities such as lifting, pulling, or pushing and no decline in ability throughout the exercises. However due to the smaller moment created by the arm about the shoulder, a disadvantage could occur in flexion, abduction, or rotation tasks. A 1981 study assessing strength of men versus women for aircraft control operations concluded that men and women had similar leg strength but women demonstrated lesser arm strength (34). Both this study and a 1973 FAA Civil Aeromedical Institute report on control force limits for aircraft of that time demonstrated that these limits defined as the required temporary and prolonged application of force to the controls for aileron, elevator, and rudder control were set too high for many female and for some male aviators (34,35). Physical training programs do demonstrate increases in female capabilities to handle these flight tasks.

A critical strength measure in the aerospace environment is the ability to exhibit sustained muscle endurance especially in high-G maneuvers. Women are capable of pull force requirements for static and dynamic ejection sequences and can safely initiate these sequences (33). The cervical stresses of added head weight particularly in the high-G environment were limiting for the women tested with regard to mask/mask-hose placement, and the ability to read lower cockpit displays and locate targets. In +4 to −4 G_z, all of the subjects experienced an impaired ability to move their heads and limitations in visual range due to the mechanics of the helmet assembly and not due to visual compromise (33). The sex differences in strength are due to differences between men and women in muscle size as estimated by lean body weight or limb cross-sectional dimensions. Women, just as men, possess a wide variety of strength characteristics.

MIXED GENDER CREW DYNAMICS

This section addresses mixed gender crew dynamics. Societal acceptance of women in all aviation roles has evolved and on occasion been aided by governmental mandates. The timeline at the start of this chapter lists some of the milestones for women in aviation. WASPs performed significant support aviation services during World War II such as towing targets, ferrying aircraft, and serving as instructor pilots among other duties. Their integration into true military aviation service to the nation took some time longer. In 1979, a legislative act gave the WASPs, well-deserved, veteran status. In the 1970s, the Navy and then Army (1973), followed by the Air Force (1976) began training women for military aviation operations. A survey study conducted by the Naval Aeromedical Research Institute in 1977 focused on the attitudes of male aviation trainees toward women in naval aviation training (36). In this study, a modified Attitude toward Women Scale (AWS) developed by Spence and Helmreich was used to determine male attitudes in naval aviation trainees versus a "control" of male college students at a Texas University (36). The instrument included 55 statements with an additional 20 questions added by naval psychologists to address specific military situations (36). The naval aviation trainees were willing to accept women as their peers and this was felt to be critical with the initiation of an all-volunteer military force. Interestingly, the authors postulated that the senior leadership who command units and formulate aeromedical and training policy should also be polled, but no report of this survey is available. The college students were less accepting of women as peers as per the AWS. In 1993, then Defense Secretary Les Aspin signed the authorization for women to enter the fields of combat aviation. In 1997, the USAF researchers conducted a semistructured clinical interview to assess female USAF pilots and their personal health, families, squadron relationships, and career stressors. Of the 114 pilots interviewed, 64 men and 50 women, an analysis of the data provided showed considerable progress in acceptance of women and their integration into military units (37). Working relationships among men and women were not characterized by gender distinctions but rather by commonality of experience, shared risks, and exposures. A key factor that is still true now is the need for adequate clinical resources to address women's health needs in order to maintain the aeromedical readiness of units. This includes having the appropriate equipment, training, and laboratory support to conduct gynecologic examinations in a discrete and comfortable manner. The overwhelming majority of men and women desired to fly in combat mainly to meet their responsibilities and training as a pilot, and even more overwhelmingly at 97% and 98%, respectively, men and women felt comfortable flying with both genders (37). Women still listed sexual discrimination as the number one stressor, but men listed greater family stress than women. With several current combat arenas now, it would be interesting to repeat this study among the services to assess the impact of extended, multiple deployments and significant combat missions with regard to crew dynamics and gender relations. In addition, the prospect of mixed gender crews in a return to the moon or extended duration Mars mission should prompt further study in this area.

OTHER GENDER-RELATED ISSUES

G Tolerance

Factors other than strength are more important for operations in present day high-performance aircraft. Endurance is more important in sustaining G_z tolerance in high-performance tasks, and Gillingham conducted the classic work on gender and G_z tolerance effects (38). In standard G_z profiles with both gradual and rapid onset, there was no difference between the sexes in relaxed or straining G tolerance. In addition, no significant difference was detected in G_z tolerance with regard to menstruation. Women had no breast-related symptoms but two episodes of urinary incontinence were reported. This finding of "G parity" has been borne out in multiple studies. In F-16 flight simulation studies using more than 30 performance measures, women were able to execute on par with men (39). However, physiologic differences with regard to adaptation to G_z stress among women and men exist. Women tend to lack adaptation with no increases in cardiac contractility or baroreceptor sensitivity resulting in greater effort with more strain versus men to sustain G_z loads (39). Further studies with similar results demonstrating a lack of difference in acceleration tolerance among genders suggest that for cockpit and aircraft design and development, requirements need not be modified for women (40). G_z tolerance decreases in the microgravity environment among both men and women. Both require countermeasures to mitigate the decrement caused by long exposures to the microgravity environment. Waters et al. has demonstrated that women have increased post–spaceflight orthostatic hypotension. This is predicted by low vascular resistance (41). Women need to employ these techniques and can satisfactorily participate in long-term space missions (42).

Urinary incontinence in the face of acceleration became an issue with Gillingham's report of two cases in his study (38). Anonymous surveys of women in regular military flying duties revealed a reported rate of incontinence similar to the general population and no effect on execution of duties in flying high-performance aircraft (43). Testing with a brief centrifuge exposure shows no significant predisposition to urine leakage and no negative effects of pelvic surgery or parity. These studies have shown that urinary incontinence is not limiting in aviation training or mission execution.

Hypoxia and Thermoregulation

In these areas, exhaustive studies featuring large and significant numbers of female subjects are lacking. Assessing the response to acute hypoxia of trained and sedentary women at varying altitudes using bicycle ergometer testing revealed that, similar to men, trained women experience a larger performance drop in maximal oxygen consumption, V_{O_2}, at altitudes of 1,000, 2,500 and 4,500 m (44). V_{O_2} is the maximal oxygen consumption generally expressed as an absolute rate of liters of oxygen per minute and reflecting an individual's aerobic capacity. Woman mountaineers tested at varying altitudes versus sea level both acutely and after longer-term exposure have similar responses to men. These include similar increases in heart rate and decreases in aerobic power ($V_{O_{2max}}$) (45,46).

Use of oral contraceptives for more than a month does affect peak exercise capacity with time to peak exercise, peak power, and V_{O_2} all moderately decreased (47). The phases of the menstrual cycle in and of itself did not have any effect on peak exercise effort among those studied.

Although differences in body mass, size, and composition exist between men and women, women have a greater density of heat-activated sweat glands. Men and women experience quantitative differences in sweating with women experiencing delayed and less-intense sweating as a means of thermoregulation. A baseline increase in body core temperature during the luteal phase of the menstrual cycle is attributed to the effects of progesterone. Female response to cold is impacted by smaller lean body mass and greater body fat content. However, no true differences in thermoregulation between men and women exist except for those associated with actual physical capacity and that of body size and composition (48).

Motion Sickness

Several studies, using both retrospective questionnaires as well as questionnaires combined with dynamic testing, report that women report both more symptoms and more intense motion sickness symptoms than men. Provocation studies have utilized tools such as optokinetic rotating drums, pseudo-Coriolis stimulation, and body rotation in a rotating chair about the yaw axis (49,50). Provocation studies provide data showing no significant difference between men and women in severity of symptoms and no physiologically measurable differences. In general questionnaires before provocation testing, women report more episodes of motion sickness (49). On the basis of societal norms, the thought is that it is more acceptable for women to report their symptoms and similarly that men underreport due to nonacceptance. The pseudo-Coriolis effects using a rotating drum with and without head motion revealed no changes in vection between men and women, but women did report more symptoms (50). Assessing both gender and ethnicity revealed comparisons to only one ethnic group making results difficult to generalize, but noting with the use of body rotation women reported more symptoms than men (51). Testing with a motion sickness questionnaire and static spatial ability tasks demonstrated that women reported higher scores on a motion sickness questionnaire and were less accurate on the tasks (52). Women may tend to report more symptoms or episodes of motion sickness, but in provocation testing there is no significant difference between men and women.

Motion sickness may vary with the hormonal and physiologic changes associated with the menstrual cycle. One small series indicated, after dynamic testing in a rotating chair and cabin assembly, that day 5 of the menstrual cycle is the point for maximal motion sickness susceptibility with a decrease in days 12 to 19, to a minimum at day 26 (53). Day 1 is defined as the first day of menstruation. With Coriolis-induced motion sickness and Doppler calf and forearm blood flow measurements, along with a subjective symptom scale, the physiologic and psychophysical measures showed no difference across the phases of the menstrual cycle (54). What are the implications of these findings? First, that motion sickness susceptibility is individualized, and although symptoms may occur, an individual's capacity to continue to function is variable—whether male or female. Second, with regard to motion sickness, there are no limitations in female activity and capability due to menstrual phases.

Decompression Sickness

Currently, rigorous study indicates that both men and women are equally susceptible to decompression sickness (DCS). While DCS could be affected by hormonal changes associated with the menstrual cycle, menopause, or use of OCPs, the literature lacks studies to support these prior claims. A study by Webb et al. studied 961 decompression exposures among 291 subjects (55). The length of profiles used ranged from 1.5 to 8 hours of exposure in 25 separate profiles of varying altitudes, duration, and activity in order to bring about symptoms. Among the 197 men and 94 women, there was no significant difference in altitude DCS risk.

Voice Communication

Female speech with its different acoustic features from males may be compromised by voice communication systems designed for male voice patterns. A study testing military aircraft cockpits in the 95 to 115 dB range demonstrated that the interpretation of female speech was lower than that for males for all experimental conditions (56). Further analysis indicated that although differences existed, these were only significant at the highest levels of cockpit noise. The difference detected at the highest levels was also impacted by the design of the communication system based on male speech spectrum, and the spectra of the cockpit noise. Use of active noise reduction technology would overcome these differences and perhaps help both genders in clear voice communication. The limited research to date indicates that there is acceptable voice communication and understanding for both genders during normal cruise operations (56).

CONCLUSION

This chapter gives the current state of literature on women's health issues and women functioning in the aviation environment. Women have and continue to contribute in all aspects of aviation. Their specific health care needs that differ from men in no way limit their ability to be continued participants and contributors.

In regard to pregnancy, the airline passenger must be assessed and assisted with planning for all aspects of travel, which include transport, food, lodging, activities, and medical support throughout an entire trip. Analysis of each phase and risk mitigation combined with appropriate prenatal care will go far in eliminating in-flight complications. Aircrew have different demands from passengers and must be more restricted in terms of duty performance during some phases of pregnancy due to environmental hazards such as G_z forces, rapid egress, altitude, among others. Policies regarding pregnancy in military aviation may benefit from standardization. Commercial space flight operators must consider the impact of pregnancy and potential hazards during training and space flight.

Gynecologic disorders such as dysmenorrhea, PMS, abnormal gynecologic bleeding, and endometriosis rarely cause sudden in-flight incapacitation and can initially be addressed by the flight surgeon. In most cases, only temporary periods of grounding will be required for treatment and flight safety.

Women, not surprisingly, vary in body size, strength, composition, and capability just as men do. In general, women have the muscular endurance and strength to accomplish required flight tasks, and targeted physical training increases these capabilities. Studies of G tolerance, hypoxia, thermoregulation, motion sickness, and DCS imply no significant difference between genders, and thereby similar susceptibility and impact of these on both men and women in flight. New and modern airframes include design features that require less input force from operators. Anthropometric issues will remain and continued research and measurements will continue to be valuable for proper design accommodations.

Social acceptance of women across the aviation spectrum increased over the last century and continues to do so. The extended space flight missions and current combat exposures offer new opportunities to study and optimize the work of mixed gender crews.

Although some research has been devoted to this area to quantitatively and empirically address the particular physiologic differences between men and women that have aerospace impact, much more must be done especially as the prospect of a return to the moon, Mars exploration, and commercial space flight loom on the horizon. Women have much more to contribute in the aerospace realm.

AKNOWLEDGMENT

We thank the following individuals who greatly assisted with our research for this new chapter, Valerie McCann, Medical Librarian for the Naval Aerospace Medical Institute, Diana Hemphill, Supervisor, Science Information Center at the United State Army Aeromedical Research Laboratory, and Mary Fran Prottsman, Science Librarian, Department of Veteran's Affairs Central Office.

REFERENCES

1. Women in Aviation International. *Current statistics of women in aviation careers in the U.S.* http://www.wai.org/resources/facts.cfm, accessed February 24, 2007.
2. Gomez Teresa. *(NASA Astronaut Selection Office) "Current astronaut number*," 8 August 2007, personal email.
3. Breathnach F, Geoghegan T, Daly S, et al. Air travel in pregnancy: the air born study. *Ir Med J* 2004;97:167–168.
4. American College of Obstetrics and Gynecology. Practice bulletin: management of preterm labor, number 43. *Int J Gynaecol Obstet* 2003;82:127–135.
5. Aerospace Medical Association. *Task force Alexandria*, 2nd ed. Virginia: Medical Guidelines for Airline Travel;. *Aviat Space Environ Med* 2003;74:A1–19.
6. Carrol D. Pregnancy and travel: travel medicine. *Clin Fam Pract* 2005;7:773–790.
7. Suh KN, Mileno MD. Challenging scenarios in a travel clinic: advising the complex traveler. *Infect Dis Clin North Am* 2005;19:15–47.
8. American College of Obstetrics and Gynecology. Committee opinion: air travel in pregnancy, number 264. *Obstet Gynecol* 2001;98:1187–1188.
9. Huch R, Baumann H, Fallenstein F, et al. Physiologic changes in pregnant women and their fetuses during jet travel. *Am J Obstet Gynecol* 1986;154:996–999.
10. Parker JT. Effects of hypoxia on the mother and fetus with emphasis on maternal air transport. *Am J Obstet Gynecol* 1982;142:957–961.
11. Newlands JC, Barclay JR. Air transport of passengers of advanced gestational age. *Aviat Space Environ Med* 2000;71:839–842.
12. Chee YL, Watson HG. Air travel and thrombosis. *Br J Haematol* 2005;130:671–680.
13. Yeast JD, Poskin M, Stockbauer J, et al. Changing patterns in regionalization of perinatal care and the impact on neonatal mortality. *Am J Obstet Gynecol* 1998;178:131–135.
14. Wilson AK, Martel MJ. Maternal transport policy. *J Obstet Gynaecol Can* 2005;27:956–963.
15. Tomimatsu T, Pereyra Pen- a J, Hatran DP, et al. Maternal oxygen administration and fetal cerebral oxygenation: studies on near-term fetal lambs at both low and high altitude. *Am J Obstet Gynecol* 2006;195:535–541.
16. Voss M, Cole R, Moriarty T, et al. Thromboembolic disease and air travel in pregnancy: a survey of advice given by obstetricians. *J Obstet Gynaecol* 2004;24:859–862.
17. Irgens A, Irgens LM, Reitan JB, et al. Pregnancy outcome among offspring of airline pilots and cabin attendants. *Scand J Work Environ Health* 2003;29:94–99.
18. Freeman M, Ghidini A, Spong CY, et al. Does air travel affect pregnancy outcome? *Arch Gynecol Obstet* 2004;269:274–277.
19. Lauria L, Ballard TJ, Caldora M, et al. Reproductive disorders and pregnancy outcomes among female flight attendants. *Aviat Space Environ Med* 2006;77:533–538.
20. Cone JE, Vaughan LM, Huete A, et al. Reproductive health outcomes among female flight attendants. *J Occup Environ Health* 1998;40:210–216.
21. Barrish R. In flight radiation exposure in pregnancy. *Obstet Gynecol* 2004;103:1326–1330.
22. Brent L. The effect of embryonic and fetal exposures to X-ray, microwaves, and ultrasound: counseling the pregnant and non-pregnant patient about these risks. *Semin Oncol* 1989;16:347–368.
23. International Commission on Radiological Protection (ICRP). General principles for the radiation protection of workers, publication 75. *Ann IRCP* 1997;27:25.
24. Tokumaru O, Haruki K, Bacal K, et al. Incidence of cancer among female flight attendants: a meta-analysis. *J Travel Med* 2006;13:127–132.
25. Dawood MY. Primary dysmenorrhea: advances in pathogenesis and management. *Obstet Gynecol* 2006;108:428–441.
26. Johnson SR. Premenstrual syndrome, premenstrual dysphoric disorder, and beyond: a clinical primer for practitioners. *Obstet Gynecol* 2004;104:845–859.
27. Premenstrual dysphoric disorder. *Diagnostic and statistical manual of mental disorders*, 4th ed. Washington, DC, American Psychiatric Association, 1994:771–773.
28. Albers JR, Hull SK, Wesley RM. Abnormal uterine bleeding. *Am Fam Physician* 2004;69:1915–1926.
29. Johnson MM. Catamenial pneumothorax and other thoracic manifestations of endometriosis. *Clin Chest Med* 2004;25:311–319.
30. Missmer SA, Cramer DW. The epidemiology of endometriosis. *Obstet Gynecol Clin North Am* 2003;30:1–19.
31. Winkel CA. Evaluation and treatment of women with endometriosis. *Obstet Gynecol* 2003;102:397–408.

32. Shender BS, Heffner PL. Dynamic strength capabilities of small-stature females to perform high-performance flight tasks. *Aviat Space Environ Med* 2001;72:89–99.
33. Shender BS, Heffner PL. Dynamic strength capabilities of small-stature females to eject and support added head weight. *Aviat Space Environ Med* 2001;72:100–109.
34. McDaniel JW. *Male and female capabilities for operating aircraft controls*. AFAMRL-TR-81–39. Wright-Patterson AFB, Ohio: Air Force Aerospace Medical Research Laboratory, 1981.
35. Lesper RC, Hasbrook HA, Purswell JC. *Study of control force limits for female pilots*. FAA-AM-73–23. Oklahoma City: FAA Civil Aeromedical Institute, 1973.
36. Baisden AG, Ambler RK, Lane NE. *An assessment of naval and marine aviation students attitudes toward women with specific reference to naval aviation*. NAMRL 1242. Pensacola: Naval Aerospace Medical Research Laboratory, 1977.
37. McGlohn SE, King RE, Butler JW, et al. Female United States Air Force (USAF) pilots; themes, challenges and possible solution. *Aviat Space Environ Med* 1997;68:132–136.
38. Gillingham KK, Schade CM, Jackson WG, et al. Women's G tolerance. *Aviat Space Environ Med* 1986;57:745–753.
39. Chelette TL, Alberry WB, Esken RL, et al. Female exposure to high G: performance of simulated flight after 24 hours of sleep deprivation. *Aviat Space Environ Med* 1998;69:862–868.
40. Navathe PD, Gomez G, Krishnamurthy A. Relaxed acceleration tolerance in female pilot trainees. *Aviat Space Environ Med* 2002;73:1106–1108.
41. Waters WW, Ziegler MG, Meck JV. Postspaceflight orthostatic hypotension occurs mostly in women is predicted by vascular resistance. *J Appl Physiol* 2002;92(2):586–594.
42. Koloteva MI, Lukianuik VY, Vil-Viliams IF, et al. +Gz tolerance by females following long-duration simulated and spaceflight microgravity. *J Gravit Physiol* 2004;11:101–102.
43. Fischer JR, Berg PH. Urinary incontinence in United States Air Force female aircrew. *Obstet Gynecol* 1999;94:532–535.
44. Woorons X, Mollard P, Lamberto C, et al. Effect of acute hypoxiz on maximal exercise in trained and sedentary women. *Med Sci Sports Exerc* 2005;37:147–154.
45. Drinkwater BL, Kramar PO, Bedi JF, et al. Women at altitude: cardiovascular response to hypoxia. *Aviat Space Environ Med* 1982;53:472–477.
46. Drinkwater BL, Folinsbee LJ, Bedi JF, et al. Response of women mountaineers to maximal exercise during hypoxia. *Aviat Space Environ Med* 1979;50:657–662.
47. Casazza GA, Suh SH, Miller BF, et al. Effects of oral contraceptives on peak exercise capacity. *J Appl Physiol* 2002;93:1698–1702.
48. Kuciba-Uscilko H, Grucza R. Gender difference in thermoregulation. *Curr Opin Clin Nutr Metab Care* 2001;4:533–536.
49. Park AH, Hu S. Gender difference in motions sickness-history and susceptibility to optokinetic rotation-induced motion sickness. *Aviat Space Environ Med* 1999;70:1077–1080.
50. Flanagan MB, May JG, Dobie TG. Sex difference in tolerance to visually-induced motion sickness. *Aviat Space Environ Med* 2005;76:642–646.
51. Klosterhalfen S, Kellerman S, Pan F, et al. Effects of Ethnicity and gender on motion sickness susceptibility. *Aviat Space Environ Med* 2005;76:1051–1057.
52. Levine ME, Stern RM. Spatial task performance, sex differences, and motion sickness susceptibility. *Percept Mot Skills* 2002;95:425–431.
53. Golding JF, Kadzere P, Gresty MA. Motion sickness susceptibility fluctuates through the menstrual cycle. *Aviat Space Environ Med* 2005;76:970–973.
54. Cheung B, Heskin R, Hofer K, et al. The menstrual cycle and susceptibility to coriolis-induced sickness. *J Vestib Res* 2001;11: 129–136.
55. Webb JT, Kannan N, Pilmanis AA. Gender not a factor for altitude decompression sickness risk. *Aviat Space Environ Med* 2003; 74:2–10.
56. Nixon CW, Morris LJ, McCavitt AR, et al. Female voice communications in high levels of aircraft cockpit noises noises-part I: spectra, levels, and microphone. *Aviat Space Environ Med* 1998;69:675–683.

RECOMMENDED READINGS

American College of Obstetrics and Gynecology. Committee opinion: guidelines for diagnostic imaging during pregnancy, number 299. *Obstet Gynecol* 2004;104:647–651.

Douglas, D. *United States women in aviation, 1940–1985*. Washington, DC: Smithsonian Institution Press, 1991.

Federal Aviation Administration Office of Aerospace Medicine, Civil Aerospace Medicine Institute. *Galactic radiation received in flight*. http://jag.cami.jccbi.gov./cariprofile.asp, accessed March 16, 2007.

Gabbe SG, Niebyl JR, Simpson JL, et al. eds. *Gabbe: obstetrics—normal and problem pregnancies*, 5th ed. Churchill Livingstone, 2007.

Jennings RT, Santy PA. Reproduction in the space environment: part II. Concern for human reproduction. *Obstet Gynecol Surv* 1990;45(1):7–17.

Katz VL, Lentz G, Lobo RA, et al. eds. *Comprehensive gynecology*, 5th ed. St Louis: Mosby, 2007.

Kelves, BH. *Almost heaven: the story of women in space*. New York:Basic Books, 2003.

Merryman, M. *Clipped wings: the rise and fall of the Women Airforce Service Pilots (WASPS) of World War II*. New York: New York University Press, 1998.

Suh KN, Mileno MD. Challenging scenarios in a travel clinic: advising the complex traveler. *Infect Dis Clin North Am* 2005;19:15–47.

Waters WW, Ziegler MG, Meck JV. Postspaceflight orthostatic hypotension occurs mostly in women and is predicted by low vascular resistance. *J Appl Physiol* 2002;92:586–594.

CHAPTER 23

An Introduction to Human Factors in Aerospace

Thomas Rathjen, Mihriban Whitmore, Kerry McGuire, Namni Goel, David F. Dinges, Anthony P. Tvaryanas, Gregory Zehner, Jeffrey Hudson, R. Key Dismukes, and David M. Musson

> The twentieth century is the age of the machine–the most complex and ingenious of which are designed to take us off our planet earth. But at the heart of these almost unbelievably sophisticated creations is the thin-skinned perishable bag of carbon, calcium and phosphorus combined with oxygen and nitrogen, a few ounces of sulphur and chlorine, traces of iron, iodine, cobalt and molybdenum added to fat and forty litres of water—Man. There he sits at the centre of this Aladdin's cave of scientific genius, the finger on the button, the tiny battery which will operate all this complexity.
>
> *David Beaty—from Naked Pilot: The Human Factor in Aircraft Accidents, 1995 (1)*

INTRODUCTION

What is Human Factors?

What is human factors? Why is it an important consideration in the context of aerospace medicine? The purpose of this chapter is to address these questions and, by way of examples, provide aerospace medicine practitioners with a broad awareness of this field that is just as critical to the success of complex human endeavors in aerospace as is physiological well-being.

Many terms and definitions are used to describe the practice of human factors. It is referred to as *human engineering, ergonomics, industrial engineering, human-systems engineering*, and other names. A popular definition was established by the International Ergonomics Association in August 2000 (2):

> "Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and other methods to design in order to optimize human well-being and overall system performance."

This definition illustrates well the essential elements of human factors. First, its goal is to enable a *system* to perform successfully by considering the role of the human in that system. Second, all interactions the human may experience are important: hardware, software, environment . . . even other humans. Third, the practice of human factors is grounded in scientific methodology.

As scientific and engineering disciplines go, human factors is still a relatively young field. Its emergence coincided with the development of increasingly complex systems that humans were called upon to operate, such as the airplane and World War II era weapons systems. Early studies were concerned with such topics as the use of instruments and automatic pilots in early aircraft cockpits, evaluation and training of pilot skills, effects of fatigue on pilot performance, as well as visual perception and display design. Currently there is a tremendous variety of specialized fields within the human factors discipline, ranging from anthropometrics and biomechanics, to sensual perception, to cognitive performance factors, to information processing, and to team dynamics.

As the definition given in the preceding text illustrates, these diverse fields have in common the goal of understanding how the human's limitations, capabilities, characteristics, behaviors, and responses will affect performance of a given system, and how that understanding can then be applied to design of the system to minimize risks and optimize performance. The anthropometry profession will determine how a space suit must be designed to accommodate the entire astronaut population. The habitability specialist will determine vehicle architectures that support operator tasks (Figure 23-1). The investigator in human information processing capabilities will specify how aircraft systems displays must be designed to maximize situational awareness under a variety of conditions. The cognitive performance expert will specify the level of automation and decision support necessary for a team to operate a complex missile defense system. These are just a few examples.

It is impossible to provide a comprehensive introduction to human factors in the context of a single book chapter. Rather, this chapter is intended to provide the aerospace medicine student with a general appreciation of the valuable contribution of human factors to the success of aerospace systems and the well-being of the humans who operate and interact with them. This will be done by exploring in greater depth just a few examples of human factors that work in aerospace. These examples are grouped into two topics: those pertaining to the understanding and characterization of human performance capabilities and the application of human factors in system design and operations.

Why is Human Factors Important to Aerospace Medicine?

The human factors discipline should be an integral part of design and development process of every system, including medical systems. Applying human factors principles in the medical domain will facilitate optimum caregiver and patient safety and system performance, and operator effectiveness will be reflected in medical device design.

There are numerous cases where system failure resulted when human factors guidelines were not considered. A report in 1999 suggested that at least 44,000 (and up to 98,000) people die in the United States each year from medical errors in hospitals (a figure greater than that recorded for road traffic fatalities, breast cancer, or acquired immune deficiency syndrome (AIDS) (3). The U.S. Food and Drug Administration (FDA) has stated that although many of these fatalities cannot be attributed to human errors involving medical equipment or systems, some certainly can be (4).

Some examples of human factors applications and benefits in medicine (5) are listed in the following text:

- Understanding human limitations early in the development of medical devices can reduce errors and avoid performance problems exacerbated by stress and fatigue
- Using human factors in a design process can reduce the costs of procuring and maintaining products
- Human factors can minimize the incidence of injury or longer-term discomfort/dissatisfaction from poor working environments
- A human factors task analysis can help identify key components of surgical skill, ensuring that students have affordable, appropriate, valid, and reliable training

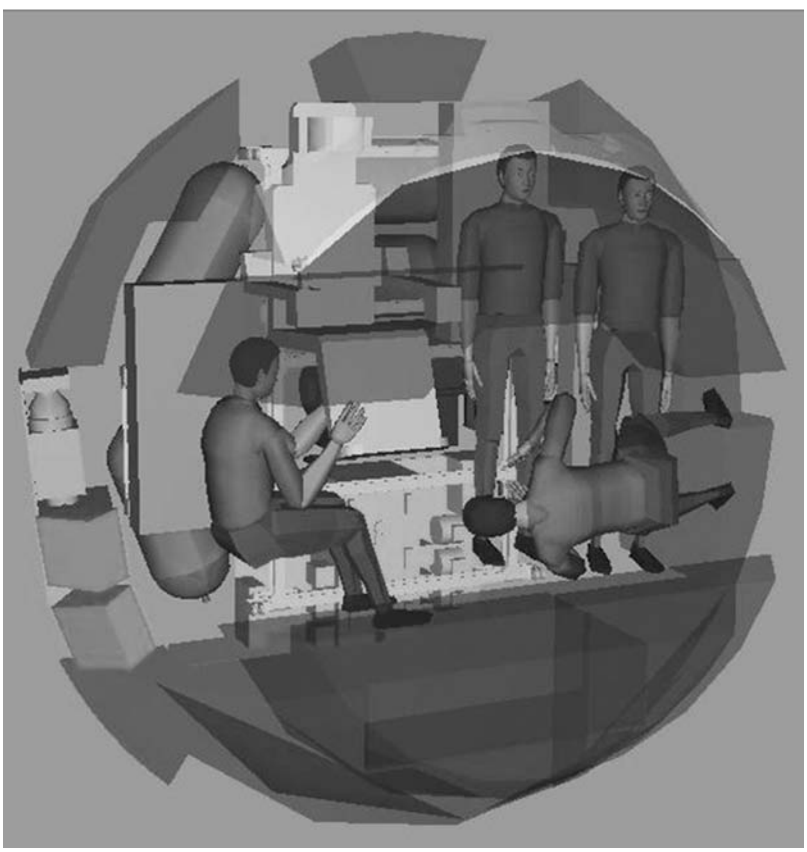


FIGURE 23-1 An example of computer human modeling analysis to assess the habitable volume adequacy of an early crew exploration vehicle (CEV) conceptual design.

To provide guidance on human factors practices in medicine, the Association for the Advancement of Medical Instrumentation produced a document titled, "Human Factors Engineering Guidelines and Preferred Practices for the Design of Medical Devices (AAMI HE48:1993)." This document covers human factors engineering processes and general recommendations for human factors engineering, workspace, signs/symbols/markings, controls and displays, alarms and signals, and user–computer interface. For instance in 1999, the Veteran's Affairs (VA) hospital system started a nationwide bar-coding program. A simplified version of bar-coding starts when a physician orders a medication. This order is transmitted to the pharmacy where a bar-code is generated. A pharmacist verifies the order and the order is sent back to the floor. A nurse on the floor uses a scanner to compare the bar-code in the patient's bracelet against the bar-code for the order. In 2006, the FDA stated that bar-code systems can reduce the number of medication errors by 50% and prevent more than 500,000 adverse drug events over the next 20 years (6).

In addition to the relevance of human factors in the medical domain, there is another reason it is advantageous for the aerospace medicine practitioner to have an awareness and appreciation of the field. As new and ever more complex air and space vehicle systems are developed, it is important for the aerospace medicine practitioner to be involved in the design process to ensure that the system operators' physiological and behavioral factors are considered and human health and well-being protected. Similarly, human factors representatives must be involved to ensure user-centered design solutions that will enable system success. Therefore, teaming between these disciplines, which are both focused on the human element, can enable leveraging, and add weight to the importance of human issues on practical, real-world system development programs.

HUMAN PERFORMANCE

Before human factors can be applied to the design of aerospace systems and operational procedures, it is necessary to understand humans' capabilities, limitations, and characteristics that will affect system performance. How big (or small) are the users of a system? How far can they reach? What colors do they best perceive in certain situations? How much can they remember under stressful conditions? How does the environment, such as temperature, atmospheric composition, and lighting, affect their endurance on cognitive tasks and physical tasks? In addition, how much variance in all of these things is there among the entire population of system users?

One should recognize the relevance of aerospace medicine concerns to the understanding of human performance, both physiological and behavioral. Fully explaining human performance characteristics will usually require an in-depth knowledge of physiological parameters. For example, the musculoskeletal system, and also psychological and cardiovascular factors, will determine strength and endurance capabilities. Moreover, behavioral and neurologic health will affect cognitive abilities. It is not typically the role of the human factors practitioner to fully explore and explain the underlying physiological drivers for human characteristics, but rather to determine that they exist and statistically bind them (for the given user population) so that designs can accommodate them. However, the student of aerospace medicine should have a unique appreciation of human performance considerations due to a unique understanding of human physiological and behavioral health in aviation and space environments.

This section provides three examples of human performance characteristics: fatigue, human error, and anthropometry. Again, these are not intended to be comprehensive, but rather to provide the reader with a general awareness of human performance considerations in aerospace applications.

Fatigue

Overview: Sleep Deprivation, Performance, and Fatigue

Fatigue is a ubiquitous risk in all modes of transportation. In operational environments, cognitive performance degrades with sleep loss, often referred to as a *fatigue effect*, which can be measured through a simple sustained attention task, the psychomotor vigilance task (7). In most cases, the effects of fatigue on performance are due to inadequate sleep and/or functioning at a nonoptimal circadian phase, but such effects can also occur as a function of prolonged work hours (time on task) and inadequate recovery times. The effects of inadequate sleep (rest) and recovery on cognitive performance are primarily manifested as increasing variability in cognitive speed and accuracy, resulting in increasingly unreliable behavioral performance. When partial or total sleep deprivation produces increased performance variability, this is hypothesized to reflect state instability, defined as moment-to-moment shifts in the relationship between neurobiological systems mediating wake maintenance and sleep initiation (7). Sleep-initiating mechanisms repeatedly interfere with wakefulness, making cognitive performance both increasingly variable and dependent on compensatory measures, such as motivation, which are unable to override increased sleep pressure without consequences (7).

Sleep deprivation induces a wide range of effects on cognitive performance. Although cognitive performance usually becomes progressively worse with extensions of time-on-task, performance on even very brief cognitive tasks that require speed of cognitive throughput, working memory, and other aspects of attention are sensitive to sleep deprivation. Moreover, divergent and decision-making skills involving the prefrontal cortex are adversely affected by sleep loss (7). These include skills critical in operational environments such as risk assessment, assimilation of changing information, updating strategies based on new information, lateral thinking, innovation, maintaining interest in outcomes, insight, communication, and temporal memory skills (7). In addition, fatigue and deficits in neurocognitive performance due to sleep loss compromise many working memory and executive attention functions important in operational environments. These include, but are not limited to assessment of the scope of a problem due to changing or distracting information, remembering the temporal order of information, maintaining focus on relevant cues and flexible thinking, avoiding inappropriate risks, gaining insight into performance deficits, avoiding perseveration on ineffective thoughts and actions, and making behavioral modifications based on new information (7).

Time zone transit, prolonged work hours, and work environments with irregular schedules contribute to performance decrements and fatigue, and therefore pose risks to safe operations. Both aviation and space environments impose such demands on their respective flight crew.

Fatigue: Aviation Settings

Operator fatigue associated with jet lag is a major concern in aviation, particularly with travel across multiple time zones. Flight crews consequently experience disrupted circadian rhythms and sleep loss. Studies have documented episodes of fatigue and the occurrence of uncontrolled sleep periods (microsleeps) in pilots (8). Flight crewmembers remain at their destination only for a short period, and therefore do not have the opportunity to adjust physiologically to the new time zone and/or altered work schedule before embarking on another assignment, thereby compounding their risk for fatigue.

Notably, although remaining at the new destination after crossing time zones for several days is beneficial, it does not ensure rapid phase shifting (or realignment) of the sleep–wake cycle and circadian system to the new time zone and light–dark cycle. Usually, pilots and flight crew arrive at their new destination with an accumulated sleep debt (i.e., elevated homeostatic sleep drive), because of extended wake duration incurred during air travel. As a result, the first night of sleep in the new time zone will occur without incident—even if it is abbreviated due to a wake-up signal from the endogenous circadian clock. However, on subsequent nights, most individuals will find it more difficult to obtain consolidated sleep because of circadian rhythm disruption. As a result, an individual's sleep is not maximally restorative across consecutive nights, which leads to increased difficulty in maintaining alertness during the daytime. Such cumulative effects are incapacitating, often taking more than a week to fully dissipate through complete circadian reentrainment to the new time zone.

The magnitude of jet lag effects is also partly dependent on the direction of travel (8). Normally, eastward travel is more difficult for physiological adjustment than westward travel because it imposes a phase advance on the circadian clock, whereas westward transit imposes a phase delay. Because the human endogenous clock is longer than 24 hours, lengthening a day is easier to adjust physiologically and behaviorally than shortening a day by the same amount of time (8). However, adjustment to either eastward or westward phase shifts often requires at least a 24-hour period for each time zone crossed (e.g., transiting six time zones can require 5–7 days), assuming proper daily exposure to the new light–dark cycle. Regardless of the direction of phase shift imposed on flight crews, if there is inadequate time to adjust physiologically to the new time zone, cumulative sleep debt will develop across days and waking performance deficits will manifest—even if crews report no such deficits (9). These facts and guidelines need to be considered when designing and implementing flight schedules for aviation crews. Current Federal Aviation Regulations (FAR) limit aviation crew scheduling to no more than 14 hours in a day (with 10 consecutive hours of rest immediately proceeding) (10), 34 hours in any 7 consecutive days (11), and 120 hours in any calendar month (11). Beyond aviation pilots, Air Traffic Control Specialists (ATCS) who work on the ground and experience the demands of 24-hour operations also report fatigue (12). Many ATCS work counterclockwise by rapidly rotating shift schedules. Such schedules not only result in difficulties in sleeping but also can produce fatigue, exhaustion, sleepiness, and symptoms of gastrointestinal distress typically found in shift workers (12). The high levels of alertness required over extended periods of time makes ATCS vulnerable to the neurobehavioral and work performance consequences of circadian disruption and sleep loss, both of which can compromise air safety.

Fatigue: Space Operations

As is true for flight crew, astronauts can also experience performance decrements and fatigue in space. Space operations couple high-level sustained neurobehavioral performance demands with time constraints, and thereby necessitate precise scheduling of sleep opportunities to best preserve optimal performance and reduce fatigue (13). Astronaut sleep is restricted in space flight, averaging only 5 to 6.5 hr/d, as a result of endogenous sleep disturbances (e.g., motion sickness, circadian rhythm desynchrony, etc.), and environmental sleep disruptions (e.g., noise, movement around the sleeper, etc.), as well as sleep curtailment due to work demands (13). Such restriction is of concern, as ground-based experiments indicate that cognitive performance deficits and fatigue progressively worsen (i.e., accumulate) over consecutive days when sleep is restricted to amounts comparable to those experienced repeatedly by astronauts (9,13).

Scheduled sleep time during space flight is primarily determined by the mission's operational needs. Sleep is regulated by a complex neurobiology involving homeostatic and circadian mechanisms that interact to determine sleep timing, duration, and structure (7). Therefore, total sleep time during space flight is usually less than scheduled time in bed. Reduced sleep efficiency, the percentage of time actually spent asleep in space flight, produces fatigue and it can therefore pose a serious risk to performance of critical mission activities. Consequently, sleep–wake schedules that optimize the recovery benefits of sleep, including reducing fatigue, while minimizing required sleep time need to be identified (13). To this end, the current practice in military aviation and some space flight operations of using sleeping medication to ensure that sleep is obtained each day needs to be evaluated for its effectiveness in maintaining performance without creating sedating carryover effects. More research to develop other effective countermeasures for fatigue in space is currently underway, including investigating the use of timed light and the use of timed naps in space (13).

Conclusion

Fatigue, sleepiness, and performance decrements, including increased reaction times, memory difficulties, cognitive slowing, and attentional lapses, result from acute and chronic sleep loss and circadian displacement of sleep–wake schedules. As such, these are common occurrences in aviation and space environments, which utilize 24-hour work situations. Neurobehavioral and neurobiological research has demonstrated that waking neurocognitive functions depend on stable alertness resulting from adequate daily recovery sleep. Therefore, understanding and mitigating the risks imposed by physiologically based variations in fatigue and alertness in the operational workplace are essential for developing appropriate countermeasures and ensuring safety of flight and space crew.

Human Error

Overview: Aerospace Operations

Human error is a very broad topic the boundaries of which are not well defined. For example, no clear boundary exists between degradation of quality of performance of diverse tasks—as for example occurs under fatigue or stress—and discrete failures of action, such as forgetting to set wing flaps before attempting to takeoff.

James Reason's book *Human Error* provides an excellent broad overview of the types of error that occur in everyday and workplace settings, the cognitive processes underlying vulnerability to error, and the ways in which organizational factors contribute to or mitigate against the propagation of errors into accidents (14). In aviation, and probably in most domains of skilled performance, most accidents are attributed to human error. An article in 1996 stated that estimates in the literature indicate that somewhere between 70% and 80% of all aviation accidents can be attributed, at least in part, to human error (15).

When professionals make errors while performing tasks not considered terribly difficult, both ordinary citizens and investigating organizations tend to assume these errors to represent some sort of deficiency on the part of the professional who made the error—that person must have lacked skill, was not conscientious, or failed to be vigilant (16). In some cases, those assumptions may be correct, but human factors research reveals that these cases are the exception rather than the rule. Both correct and erroneous performances are the product of the interaction of events, task demands, characteristics of the individual, and organizational factors with the inherent characteristics and limitations of human cognitive processes.

Some level of error is inevitable in the skilled performance of real-world tasks, such as flying airplanes, operating in emergency rooms, or driving automobiles. For example, Helmreich et al. have found that airline flight crews make one or more errors in approximately two third of flights observed (17). (These figures are probably undercounts because observers cannot detect all errors.) Because the performance of even the most skilled of experts is fallible, some may argue that automation should replace humans whenever possible. However, this perspective ignores the realities of the human tasks and the situations in which they are performed.

Computers can perform some tasks much faster and more reliably than humans, and those tasks should be assigned to computers. Nevertheless, human judgment is required for situations involving novelty, value judgments, or incomplete or ambiguous information. One would not want the decision of whether to divert a scheduled flight because of a sick passenger to be made by a computer! However, the very reasons that these tasks require human judgment make it unlikely for that judgment to be always correct.

Most errors made by professionals do not result in accidents, either because the errors do not have serious consequences or because the errors are caught and mitigated. Airline operations, for example, have extensive systems of defense to prevent or catch errors (e.g., the use of checklists and having the two pilots in the cockpit cross-check each other's actions). When accidents do occur it is typically because several factors interact to undermine defenses which the organizations have erected to catch errors. This interaction is partly random, which makes it hard to prevent, as the number of factors that might interact is very large.

Illustrative Description

Because space does not permit a full review of the large research literature addressing the issues described earlier, we will briefly summarize a recent study that illustrates the nature of the errors of skilled experts, the causes of those errors, and possible countermeasures (16). The authors of this study reviewed the entire set of 19 major accidents in U.S. airlines occurring over a 10-year period, and in which the National Transportation Safety Board (NTSB) found flight crew error to be causal. The study examined the actions of each crew as the flight evolved, asking why might any highly experienced crew, in the situation of the accident crew, and knowing only what the accident crew knew at each moment, be vulnerable to doing things in much the same way as the accident crew.

The study found that almost all the events leading to these accidents clustered around five themes, defined as much by the situations confronting the pilots as by the errors they made:

1. Inadvertent slips and omissions when performing familiar tasks either under routine or challenging conditions. Examples of these slips and omissions are forgetting to

arm spoilers before landing, forgetting to turn on pitot heat, and forgetting to set flaps to takeoff position. These omissions are examples of prospective memory errors, a field of research that has recently burgeoned (18). Under benign conditions, these errors are usually caught before they become consequential. However, in the presence of other factors such as interruptions, time pressure, emergencies, fatigue, or stress these errors are much less likely to be caught, sometimes with dire consequences.

2. Inadequate execution of non-normal procedures under challenging conditions. Pilots in several accidents failed to correctly execute procedures for recovering from a spiral dive, from a stall, and from wind shear. Pilots receive training on these procedures, but studies have shown that in actual flight conditions, many pilots have trouble performing the correct response. One shortcoming of existing training for upset attitude recovery is that in simulation training pilots are expecting the upset and they typically know which upset they are about to encounter. Nevertheless, in the real world of surprise, confusion, and stress it is far more difficult to identify the nature of the upset and select and execute the correct response. Another shortcoming is that airline training does not allow pilots to practice responding to upsets often enough for responses to become automatic.
3. Inadequate response to rare situations for which pilots are not trained. These situations included a false stick–shaker activation just after rotation, an oversensitive autopilot that drove the aircraft toward the ground near decision height, anomalous indications from airspeed indicators that did not become apparent until the aircraft was past rotation speed, and an uncommanded auto-throttle disconnect whose annunciation was not at all salient. The first three of these four situations required quite rapid responses—the crews had at most a few seconds to recognize and analyze a situation for which they were not trained and had never encountered, and within these few seconds, the crew had to choose and execute the appropriate action. Here too surprise, confusion, stress, and time pressure undoubtedly played a role.
4. Judgment and decision making in ambiguous situations. An example of judgment in ambiguous situations is continuing an approach toward an airport in the vicinity of thunderstorms, exemplified by the accident at Charlotte in 1994. In this accident, the crew was very much aware that they might have to break off their approach and actively make plans for how they would handle this. Unfortunately, by the time it became apparent that they needed to go around, they were already in wind shear, and several other factors interfered with their attempt to recover.

   No algorithm exists for crews to calculate exactly how far they may continue an approach near thunderstorms before it should be abandoned. Company guidance is typically expressed in rather general terms, and the crew must make this decision by integrating fragmentary and incomplete information from various sources, and improvising. When an aircraft crashes while attempting an approach under these conditions, the crew could be found at fault. Yet there are reasons to suspect that the decision making of the accident crews was similar to that of crews who were more fortunate. A Lincoln Laboratory study of radar data at Dallas/Fort Worth revealed that when thunderstorms are near the approach path it is not uncommon for airliners to penetrate the cells. Moreover, in the investigation of wind shear accidents it is not uncommon to find that another aircraft landed or took off only a minute or two ahead of the accident aircraft without difficulty. Both crews had the same information and both made the same decision, but rapidly fluctuating conditions allowed one to operate without difficulty and caused the other to crash. Removing the ambiguity through improved procedural norms for operating in these situations, and consistent application of these norms, might reduce accidents that occur during highly dynamic environments where both judgment and luck currently play a role.
5. Deviation from explicit guidance or Standard Operating Procedure (SOP). An example is attempting to land from an unstabilized approach resulting from a "slam-dunk" clearance, as occurred in an accident at Burbank in 2000, in which the airplane overran the runway and ended up ignominiously at a gas station (16). (Slam-dunk refers to situations in which controllers put the aircraft in a position of being so high and fast that it is difficult for pilots to stabilize aircraft speed, descent rate, and configuration in time to land safely.) If the company has explicit stabilized approach criteria, these deviations may seem simply to be willful violations. However, even here the situation may not be as simple as it seems. Does the company publish and train the stabilized approach criteria as an absolute bottom line or merely as guidance? What are the norms for what most pilots actually do in the company and in the industry? Pilots are influenced by company pressures for on-time performance and fuel economy, which conflict with formal guidance for operations. Also, some pilots may not have been trained to understand that correcting an unstabilized approach imposes so much workload that the flying pilot does not have enough mental capacity left over to reliably assess whether it is possible to get the aircraft stabilized by touchdown.

The study also identified a range of cross-cutting factors that contribute to the vulnerability of pilots in making the sorts of errors described earlier. In many accidents, several of these cross-cutting factors were working simultaneously. Six of these factors are as follows:

1. Situations requiring rapid response. Surprisingly, approximately two thirds of these accidents involved situations in which the crew had only a matter of seconds to choose and execute the appropriate response. Examples include upset attitudes, false stick–shaker activation just after rotation, anomalous airspeed indications at rotation, pilot-induced oscillation during flare, and autopilot-induced oscillation

at decision height. This finding is surprising because most threatening situations encountered in airline operations allow the crew time to think through what to do, and in these situations it is important to avoid rushing. We concluded that these 19 accidents included a disproportionately high number of situations requiring very rapid response because, although these situations are quite rare, when they do occur it is extremely difficult for crews to overcome their surprise, assess the situation, and quickly execute the appropriate response. Human cognitive processes simply do not allow pilots to reliably assess novel situations quickly and make the right response reliably.

2. Challenges of managing multiple tasks concurrently. These challenges appeared in the great majority of accidents. In some cases workload and time constraints were high in the final stages of the accident sequence, and the crew became so overloaded that they failed to recognize that they were losing control of the situation and failed to break off the approach. The accident at Little Rock in 1999 is a case in point, in which an MD-80 crew became so overloaded dodging the weather that they failed to consider the advisability of continuing the approach, failed to arm the spoilers, and failed to adjust the thrust reverser deployment for wet runway conditions. Overloaded crews often become reactive rather than proactive, responding to each new demand on their attention; consequently, little mental capacity is left to think strategically. Monitoring and cross-checking fall by the wayside.
3. However, in many of these accidents, adequate time was in principle available to perform all required tasks. Unfortunately, the inherent difficulty in reliably switching attention back and forth among concurrent tasks impaired performance in these accidents. Even experienced pilots are vulnerable to becoming preoccupied with one task to the neglect of other tasks, and they also forget to complete a task when interrupted or distracted or when forced to defer a task out of its normal sequence.
4. Plan continuation bias. This is a powerful but unconscious cognitive bias to continue the original course of action or a habitual course of action even when conditions change, making that original plan of action not to be a good idea. The pilots do not fully understand the cognitive mechanisms that underlie plan continuation bias, but we suggest that several factors come into play. Individuals may develop an inaccurate mental model of the level of risk in a particular situation because they always got by in the past, not realizing how close they came to the edge of the envelope. Norms come into play strongly here—pilots tend to do what their peers do, especially the flight directly in front of them. Information is often incomplete or ambiguous and generally arrives piecemeal, which makes it hard to integrate, especially under heavy workload, stress, or fatigue. Expectation bias makes us less likely to notice cues that the situation is not what we expect from past experience. In addition, there are subtle and not so subtle pressures from competing organizational goals—pilots are certainly aware that on-time performance and fuel costs directly influence the survival of their companies.
5. Stress. Stress probably undermined the performance of many of these flight crews; however, it is rather like fatigue in that it is hard to find the smoking gun after the accident. Stress, which is a normal physiological response to threat, hampers skilled performance by narrowing attention and reducing working memory capacity required to execute tasks. In particular, the combination of stress and surprise with requirements to respond rapidly and to manage several tasks concurrently, as occurred in several of these accidents, is a lethal setup.
6. Social and organizational issues. These issues may have a pervasive influence. For example, how operations are actually conducted on the line may deviate from the ideals expressed in flight operations manuals, for many reasons. Unfortunately, little data is available to accident investigators on the extent to which the accident crews' actions were typical or atypical of other pilots in the situation they faced. Also, pilots may not be consciously aware of being influenced by competing goals that they have internalized, for example, the trade-offs between on-time performance and conservative response to ambiguous situations. It is possible for pilots to receive mixed messages: On the one hand, they are supposed to follow company guidance on procedures, on the other hand they may be told, implicitly or explicitly, that the company's survival depends on constraining fuel costs and upholding on-time performance.

This study has implications for understanding pilot error and for preventing future accidents. Foremost is that errors and accidents are best thought of as vulnerabilities and failures in the overall system rather than as deficiency on the part of pilots who met with accidents. Terms such as *complacency* and *lack of situation awareness* are labels, not explanations for why errors occur. Errors occur on almost all flights, but in the vast majority of flights, these errors are prevented from causing accidents. In aviation, a large number of safeguards have been erected to detect and mitigate errors, especially crew resource management (CRM), discussed later in this chapter. The latest version of CRM emphasizes threat and error management (TEM). The methods airlines use to achieve an extraordinarily high level of safety can be adapted to other fields, such as medicine and nuclear and chemical plant operations.

Conclusion

From a systems perspective, the best way to reduce vulnerability to errors and accidents is to design the overall operating system for resilience to equipment failures, unexpected events, uncertainty, and human error. Equipment, procedures, and training must be designed to match human operating characteristics, rather than expecting humans to adapt to the quirks of the equipment they must operate. Pilots can be trained to recognize situations in which they are vulnerable to error and can be provided techniques for reducing vulnerability to specific forms of errors. All organizations—not just airlines—should periodically conduct systematic reviews of their operating procedures and revise procedures that are conducive to error.

Finally, organizations should recognize that efficiency and production throughput are pressures that often compete against safety. Organizations must recognize this conflict and take responsibility for establishing policies, procedures, and reward structures that truly support, giving safety the highest priority.

Anthropometrics

Overview

> "Traditional Anthropometric measurements of bone and other tissue, though of scientific and practical value, are not functional; their applicability is limited to those rather standard conditions which exist when they are taken and they may not be transferred to other postures. Postural and kinematic problems may only be solved by a functional system of measurements."
>
> W.T. Dempster—from the Space Requirements of the Seated Operator, 1955 (19)

Anthropometrics is the measurement of human bodily characteristics (20). Everyone has seen long lists of anthropometric dimensions, usually presented as tables of percentile values. Ranges of joint motion, reach envelopes, strength profiles, and a great deal of other information on human capabilities and variation are presented in this manner as well. These data are commonly used in specifications for equipment design and to describe population variability. In reality, data of these types are of limited use. Current methods in anthropometry and biomechanics are more along the lines of Dempster's vision. When designing and testing items of equipment, a systematic approach is used which includes the following:

- Defining the anthropometry of the user population in multivariate space
- Setting functional requirements, which operators of the equipment must be able to perform, or levels of physical stress they must endure
- Testing the ability of the user population to meet the functional and safety requirements of the equipment
- Developing predictive equations for modifying the equipment or selecting future users of the system

Designing aircraft cockpits to accommodate the wide range of body sizes existing in the U.S. population has always been a difficult problem for crew station engineers. The approach taken in the design of military aircraft has been to truncate the range of body sizes allowed in flight training, and then to develop standards and specifications to ensure that most of the remaining pilot sizes are accommodated. Accommodation in this instance is defined as the ability to perform the following:

- Adequately see, reach, and actuate controls
- Have external visual fields so that the pilot can see to land, clear for other aircraft, and perform a wide variety of missions (ground support/attack or air to air combat)
- Finally, if problems arise, the pilot has to be able to escape safely

Each of these areas is directly affected by the body size of the pilot. Assignment of individuals to aircraft in which they are poorly accommodated puts them at increased risk for mishap. Although currently only a few accident investigations have reported body size as the sole cause of the mishap, there have been many mishaps where body size may have been a contributing factor. Methods for correcting this problem by predicting pilot fit and performance in the United States Air Force (USAF) aircraft based on anthropometric data were developed by the military in the 1990s. These methods, discussed in the subsequent text, can be applied to a variety of design applications where fitting the human operator into a system is a major concern.

Illustrative Description

Anthropometric Profiles

What are the anthropometric profiles of the male and female user populations, and how do we represent this variability?

Answering this question usually involves locating appropriate existing datasets or the creation of subsets from similar samples. As military anthropometric surveys are becoming outdated (21), many researchers are using civilian samples such as the 1999 Civilian American and European Surface Anthropometry Resource (CAESAR) (22). Owing to fitness differences between civilian and military populations, the CAESAR survey has to be restructured to match USAF demographic and fitness profiles. Generally, this means selecting individuals from the survey based on height, weight, age, race, and gender.

Once the population of interest has been defined by a sample, the traditional method of describing anthropometric variability uses lists of 5th and 95th percentile values for a large number of dimensions. Nearly all current USAF aircraft were designed in this way. Unfortunately, this method leads to many errors and misconceptions as percentiles are not additive and do not describe variability in body proportions. A multivariate technique for describing body size and shape variability is now used to specify new aircraft designs and existing aircraft modifications.

This method uses a Principal Components Analysis technique developed by Meindl et al. (23). Principal Component Analysis allows reduction of a long list of measurements to a smaller, more manageable number, and then enables designers to select the desired percentage level of a population to be accommodated. This desired percentage of the population is represented by a small set of selected boundary conditions, which take into account not only size variance but proportional variability as well. Table 23-1 lists the finalized, multivariate boundary cases that were developed for the Joint Primary Air Training System (JPATS) aircraft that later became known as the *T-6 Texan II*. These boundary cases represent individuals who are uniformly large or small, as well as those whose measurements combine, for example, small torsos with long limbs, and vice versa.

TABLE 23-1

Joint Primary Air Training System (JPATS) Multivariate Cases 1–7

	Case 1 Small	*Case 2 Medium Build Short Limbs*	*Case 3 Medium Build Long Limbs*	*Case 4 Tall Sitting Height Short Limbs*	*Case 5 Overall Large*	*Case 6 Longest Limbs*	*Case 7 Overall Small*
Thumb tip reach	27	27.6	33.9	29.7	35.6	36	26.1
Buttock-knee length	21.3	21.3	26.5	22.7	27.4	27.9	20.8
Knee-height sitting	18.7	19.1	23.3	20.6	24.7	24.8	18.1
Sitting height	32.8	35.5	34.9	38.5	40	38	31
Eye height sitting	28	30.7	30.2	33.4	35	32.9	26.8
Shoulder height sitting	20.6	22.7	22.6	25.2	26.9	25	19.5
Shoulder breadth range	14.7–18.1	16.4–20.6	16.2–21.2	16.8–21.7	16.9–22.6	16.8–22.5	14.2–18.0
Chest depth range	7.4–10.9	6.9–10.6	7.2–11.3	7.1–11.0	7.3–12.1	7.4–12.2	7.2–10.2
Thigh circumference range	18.5–25.0	17.1–25.0	20.2–27.6	17.6–26.3	18.6–29.2	19.1–29.7	17.8–25.2

If a workspace is designed to enable all these cases to operate efficiently, then all other less extreme body types and sizes in the target population should also be accommodated. However, as Hendy (24) suggests, for some applications many more model points must be considered. The representative cases may need to be distributed throughout the sample—rather than only on the periphery. This is particularly true in clothing applications. A designer would not want to base a design solely on the most extreme anthropometric combinations. Hence, the actual product being designed dictates the measurements of interest, the percentage of accommodation required, and the number of cases developed.

In addition, principal component analysis cannot describe all the variability in body size that must often be taken into account for a particular design. Some variability in the measurements is lost when a reduced number of components are used. In addition, it can be a needlessly complex technique for calculating some dimensions, for example, when only minimum or maximum values need be known. In the case of shoulder breadth, for example, it does not matter if the widest or most narrow shoulders are found on an individual with a given sitting height. Shoulder breadth is used to assure that wide shoulders clear the sides of the cockpit during ejection, and that narrow shoulders fit the restraint system properly. While measurements such as shoulder breadth must be considered in a cockpit design, the largest and smallest expected values for the measurement can be considered separately from the combinations of torso and limb size discussed earlier. Simple listing of the extreme values for measurements that are not related to seat position will suffice. However, this does not mean that a return to percentiles for these measurements is warranted. Dropping a significant percentage of a population for each measurement is a serious error. The values used should be at or very near the population minimum and maximum values for a given measurement. It must be reemphasized that selection of the measurements deemed important in a design application may be the most important step in the entire process.

Operational Requirements

What tasks must be performed in an aircraft to safely and effectively operate it?

These requirements establish the pass/fail criteria that pilots must perform to safely operate that particular aircraft. Although it is obvious that all controls must be reachable in an aircraft during normal operation, understanding pilot reach issues during worst-case scenarios, or emergency conditions, is essential. In an emergency, the inertial reel restraint system may lock, or, due to adverse G forces, the pilot may be pushed into a position from which it is difficult to reach a particular control. For these reasons (critical reaches as well as minimum visual fields to see the landing zone, or other aircraft in a formation) a critical tasks list must be defined. Anthropometric measures are associated with the performance of these critical tasks. These requirements become the pass/fail criteria during accommodation evaluations, or mapping, of the cockpit.

Cockpit Mapping

Can the performance of an individual in a particular cockpit be accurately predicted from their anthropometric measurements, and can these data be used to predict accommodation percentages for an entire population?

Once the operational requirements have been defined, cockpit mapping is used to make measurements on a sample of subjects performing the requirements in a crew station. The sample data are analyzed to produce regression equations that quantify the link between performance and anthropometry. When combined with the list of critical tasks discussed earlier, these data can be used to assess the impact of accommodation limits on the entire population in terms of the percentage that can or cannot operate a particular aircraft safely. As a collective, these regression equations comprise an algorithm that takes into account the adjustment ranges of the seat and controls, and is used to predict performance levels for an individual or a population. On the basis of our previous experience, at least 20 test subjects representing the range of variation as well as the extremes of body size within the potential user population are needed to perform the cockpit evaluation. By combining the algorithms developed on this sample with datasets constructed to represent any current or future pilot population, the severity of the nonaccommodation problem that exists can be determined.

Actually, the subjects are used as human "tools" to establish limits of body size accommodation. Each subject is measured both statically in the laboratory for anthropometry, and as they perform the list of operational requirements in the cockpit. Excess and miss distances are measured so that minimum ability levels can be calculated.

Generally, seven aspects of anthropometric accommodation are examined, which include the following:

1. Overhead clearance
2. Rudder pedal operation
3. Internal and external visual field
4. Static ejection clearances of the knee, leg, and torso with cockpit structures (i.e., canopy bow)
5. Operational leg clearances with the main instrument panel
6. Operational leg clearance with the control stick motion envelope and pilot's ability to attain the full range of stick travel
7. Hand reach to controls

In some aspects of accommodation (e.g., overhead clearance and vision), anthropometric relationships are obvious and simple. Overhead clearances are directly related to sitting height. Vision out of the aircraft, (primarily over-the-nose vision), is directly related to sitting eye height. For these issues, multiple anthropometric dimensions are unnecessary to explain accommodation levels.

Other measures of accommodation are more complex. For example, operational clearance of the body with the control stick motion envelope can be restricted as the stick is pulled aft. In addition, it is possible for collision between the stick and thigh as the stick is pushed left or right to roll the aircraft. This results in limited aileron movement, reduced roll rate, and could change pilot control of aircraft flight characteristics at the wrong time. Limitation of stick motion is influenced by sitting eye height, thigh circumference, and buttock–knee length. The relationship between the upper seat positions (used by pilots with small sitting eye height) and thigh size seems to be the most critical because of potential interference with instrument panel. In Figure 23-2, stick clearance problems can be visualized by imagining that the motion of the upper end of the control grip is similar to the base of an inverted pyramid.

In aircraft equipped with a traditional center control stick, as the seat is raised to improve external vision, the pilot's legs move higher into a region where there is more side-to-side stick travel for a given stick input. Extremely large-sized pilots will typically use the full-down seat position, and the control stick is usually so far above the thighs that interference does not occur. However, small-sized pilots are typically adjusted as high in the seat as possible to gain adequate over-the-nose vision. In this seat position, the stick often contacts their

FIGURE 23-2 Control stick range of motion.

thighs. In addition, pilots with long legs are typically able to spread their knees apart, making a greater space available between the thighs for control stick movement. Small-sized pilots may not be able to spread their legs while keeping their feet on the rudder pedals.

For these reasons, subjects of various sizes are tested with the seat adjusted to numerous positions in the cockpit. Enough data are taken to enable the prediction of an individual's ability to be accommodated. For example, if a subject with the seat adjusted to the full-up position misses reaching to the landing gear handle by 1.5 in., that subject's anthropometric dimensions will be regressed against the 1.5 in. miss distance for that seat position. Many subjects must be run in a variety of seat positions to calculate all the different combinations of size and seat positions possible for reaching controls. We use a similar approach for many of the other aspects of accommodation listed in the preceding text. Regression provides a best-fit estimate for the sample measured. The estimate is similar to the "average" answer for a group of people of the same size. These data should therefore be considered accurate estimates, not exact data points.

Discussion

There are relatively large percentages of current pilots who are not well accommodated in older USAF aircraft. For example, the T-38A (fighter training aircraft) design was based on 5th and 95th percentile male pilot data from the 1950 USAF anthropometric survey. That design philosophy accepted the premise that 10% of the pilot population could have accommodation problems. Our testing of that aircraft showed that only 12% of current large and small male pilots are beyond these bounds. This is surprisingly good given the nonadditive nature of percentiles (22).

The high percentage of female pilots (37%–50%) not accommodated in the T-38 is also not surprising. Statistical analyses have confirmed that a high percentage of female pilots fall below the 5th percentile male pilot values for many measurements. These pilots have had to learn to compensate for their body size by stretching, flying with a loose harness, or have not been in an emergency situation where immediate access to full rudder or throttle was required to survive.

In addition to testing pilot fit in the aircraft, all items of equipment must also be tested to determine their effects on pilot performance and safety. Fit mapping of clothing and protective equipment is carried out with methods similar to those described here. Fit requirements must be defined quantitatively, anthropometric measurements must be related to those requirements, and subject testing must be carried out to determine (and later to predict) acceptable fit.

A related area that is also considered is that of *dynamic fit*. This overlaps with the traditional fields of biomechanics and biodynamics. Although a pilot may be able to actuate all aircraft controls when on the ground—while wearing the appropriate protective equipment—is it possible to do so when under adverse G conditions? When performing certain flight maneuvers, such as a tight high-speed turn, the pilot as well as everything on the pilot becomes extremely heavy. This creates a very different environment than the static tests discussed earlier. The biodynamic responses of the human body in dynamic testing are directly related to anthropometry and cannot be overlooked. A long-thin neck topped with a large-heavy head will react differently under loading than a short-thick neck topped with a small- light head.

The JPATS specification required accommodation of smaller females and larger males than probably any other aircraft in history. This posed new challenges in the accurate representation of human response to dynamic environments and ejection. Given the much broader range of pilot size and shape, new ejection seat test manikins had to be developed for the program. The JPATS anthropometric cases, listed in Table 23-1, were the basis for not only the size and proportions of these manikins but also their static mass distribution properties (25). These manikins became human surrogates for much of the dynamic testing of this aircraft system. G forces are even higher during an ejection. For that reason, a great deal of testing of human tolerance and pilot equipment was performed on these manikins using devices such as the horizontal impulse accelerator (sled track) and the vertical drop tower (26). These devices help track the effects of rapid acceleration and deceleration on the human body as well as the performance of the protective equipment placed on the pilot. A 12-lb head in a 1-G environment weighs more than 100 lb in a 9-G turn. A helmet with 4-lb mass in 1-G conditions can weigh as much as 36 lb when in a 9-G turn. While this can obviously cause a great deal of stress to the structures of the neck, it also has a large effect on the fit of the equipment. If this helmet fits the pilot poorly, it will move dramatically on his/her head during this maneuver. In this example, the distribution of mass in items of equipment has to be determined as well. During a high G turn, imagine the dynamic difference between a 10-lb weight balanced over the center of gravity of your head and 10 lb hanging off your forehead.

Some dynamic research must still be performed using human subjects. For example, pilot reach under high G forces in both negative and positive directions has been investigated using the Dynamic Environment Simulator (centrifuge) in order to quantify these difficulties. These forces must be considered when accommodation levels are being tested (27).

Conclusion

While the examples discussed here were geared toward evaluation of cockpit accommodation, the methodologies described can be applied to a variety of design applications where fitting the human operator into a system is a major concern. Examples of such applications are flight suits, helmets, and oxygen masks. A systematic approach, which includes defining the user population, setting functional (or fit) requirements for operators, testing the ability of the user population to perform the functional requirements, considering the dynamic environment of the operator, and where necessary, developing new design criteria and methods that assure accommodation, is the key to a successful anthropometric design.

DESIGN AND OPERATIONS

The previous section provided examples of how human performance characteristics must be understood and considered if an aerospace system is to succeed. The human factors field is constantly evolving and improving its knowledge base and reference information. However, the human factors discipline does not stop here. Another focus of aerospace human factors is directly applying proven methodologies to the design process and operational domain.

It would be impossible to catalog design reference standards for every human interface situation that will occur in aerospace. Although exhaustive tables on anthropometric dimensions can be measured and published, what are the infinite varieties of body postures possible in a space suit or aircraft cockpit? While heuristics for display design can prove very useful for typical applications, what about for extreme environments such as rapid day/night lighting cycles in an orbiting spacecraft? Moreover, when human behaviors and interactions can be modeled and predicted based on personality profiles and such, what about situations where company policy or governing rules add new influencing factors?

For these and countless other situations for which reference material on human characteristics are not adequate, the human factors discipline provides methodologies, tools, and processes to directly apply human-centered approaches to design and operational implementation. Structured user evaluations, training techniques, task analyses, application-specific human-systems requirements development, and human modeling are just some general examples. This section provides three specific examples of the application of human factors in the design of an operation: user interfaces, CRM, and unmanned aircraft systems (UASs).

User Interfaces

Overview

A user interface is anything a user interacts with (e.g., computer, tool, device, or other part of the system). The user interface enables the user to pass information (e.g., mouse click to close a window) between the user and the system. One of the key considerations of human factors is design of the user interfaces in order to provide optimum means of interactions between the users and the systems including hardware, software, procedures, instructions, and training. The overall objective is to match the user capabilities and limitations with the systems they are interacting with to enhance effectiveness, efficiency, and safety of these interfaces (28).

A good user interface is a good fit between need and solution as well as between the user and the system that makes it possible for the user to perform his/her task more reliably and with fewer errors. These interfaces are "useful" and "usable," thereby, easy to use, learn and remember, safer (with less errors), and more satisfying (subjectively pleasing). Usability applies to all aspects of a system with which a human might interact, including operations and maintenance (29).

How to determine usability?

The following are the four needs to ensure usability as per Gould and Lewis (1985: 300–311):

1. Establish an early and continuous focus on users.
2. Integrate consideration of all aspects of usability.
3. Test versions with users early and continuously.
4. Iterate design (test-modify-retest).

There are a number of methods that can be used to evaluate the "usability" of the systems. These methods are heuristic evaluation, performance measures, thinking aloud, observation, questionnaires, interviews, focus groups, logging actual use, and user feedback (29).

Heuristic evaluation is systematic critique of a user interface to identify usability issues using well-established guidelines and standards. They involve a small group of evaluators to review the interface and determine its compliance with these guidelines, standards, and principles ("heuristics" such as consistency, good caution and warning labels/messages, minimizing human workload). Whereas performance measures through usability testing facilitate collection of objective data on how well users perform, such as task completion times and errors, the thinking aloud method facilitates documenting the users' point of view on the user interface–related issues. Observations, questionnaires, interviews, and focus groups also help capture systematically user inputs and perceptions on the user interface. Logging actual use helps with determining most frequently used interface features, whereas user feedback can help track changes in user requirements and opinions (29).

Mostly, these methods supplement each other and therefore different combinations should be used based on the problem at hand and constraints such as available number of users or usability personnel. The most common combination is heuristic evaluation, thinking aloud, and/or usability testing. Typically, heuristic evaluation is used to clean up the user interface issues, whereas usability tests are used to validate the modified design and verify the compliance with the requirements and guidelines.

Illustrative Description

The respiratory support pack (RSP) is a medical pack onboard the International Space Station (ISS) that contains much of the necessary equipment for providing aid to a conscious or unconscious crewmember in respiratory distress (Figure 23-3). Inside the RSP lid pocket is a 5.5 by 11 in. paper procedural cue card, which is used by a

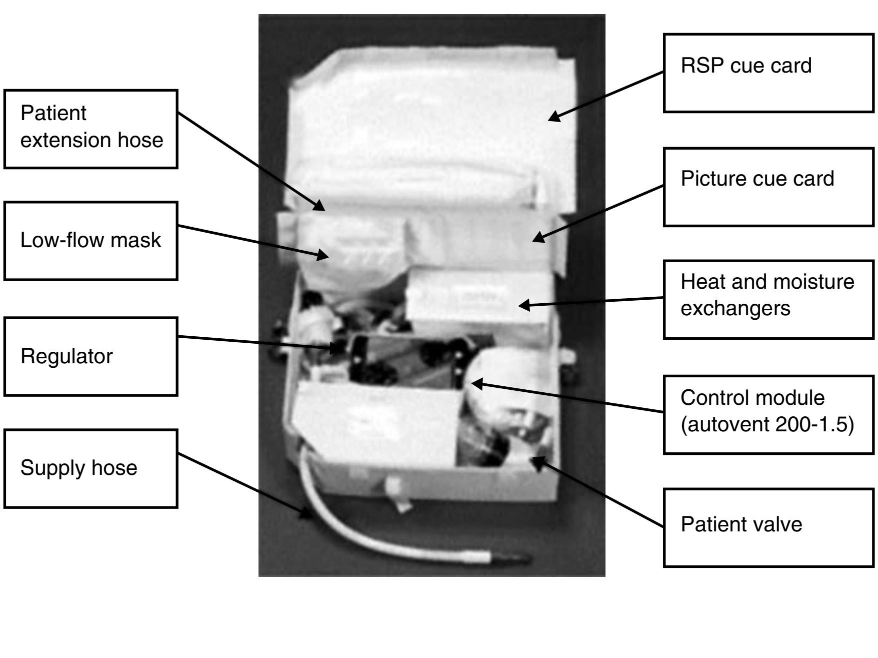


FIGURE 23-3 International Space Station respiratory support pack.

crew medical officer (CMO) to set up the equipment and deliver oxygen to a crewmember. In training, crewmembers expressed concerns about the readability and usability of the cue card; consequently, updating the cue card was prioritized as an activity to be completed. The Usability Testing and Analysis Facility at the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) evaluated the original layout (Figure 23-4) of the cue card, and proposed several new cue card designs based on human factors principles.

Approach

The approach taken for the assessment was an iterative process. First, to completely understand the issues with the RSP cue card, crewmember's post–training comments regarding the RSP cue card were taken into consideration. Over the course of the iterative process, the procedural information was reorganized into a linear flow after the removal of irrelevant (nonemergency) content. Pictures, color-coding, and borders were added to highlight key components in the RSP to aid in quickly identifying those components. There were minimal changes to the actual text content.

Three user evaluations were conducted using a total of 34 non–medically trained JSC personnel in order to approximate a scenario of limited CMO exposure to the RSP equipment and training (which can occur 6 months before the mission). In each study, participants were asked to perform two respiratory distress scenarios using one of the cue card designs to simulate resuscitation (using a mannequin along with the hardware).

The two "patient" evaluation scenarios were adapted from those currently used for ISS crew medical training. One involved a conscious patient and the other an unconscious patient. The purpose of the two scenarios was to utilize most of the equipment in the RSP.

A questionnaire was provided to the participants after they completed both scenarios to assess the usability of the cue card and RSP equipment; specifically, the layout of the cue card, amount of information, items that were extraneous or missing, as well as general questions about the design of the RSP hardware and pack. The questionnaire was based on a 7-point Likert scale with "1" indicating strongly disagree and "7" indicating strongly agree. Open-ended questions also provided the opportunity for participants to recommend cue card ideas and suggestions for RSP hardware changes. Participants were also asked what strategy they followed in using the cue card and medical equipment that were unfamiliar to them.

The hardware used in all the evaluations consisted of the following:

1. RSP
2. Advanced life support pack (ALSP), which housed the Ambu bag
3. A ziploc bag, which served as the intubating kit/airway (IK/A), and housed the intubating laryngeal mask airway (ILMA) equipment
4. A box representing the defibrillator
5. A box with a picture of the O_2 connector representing the Crew Health Care System (CHeCS) rack O_2 connection
6. A patient mannequin

General Procedure/Experimental Design

Each participant was provided with the evaluation description and asked to sign the consent form. Each participant performed two respiratory scenarios, one with a conscious patient, and one with an unconscious patient, using one cue card to perform both scenarios. The scenarios were adapted from respiratory scenarios used in ISS medical training. The order of scenario presentation was changed for every other participant. The type of cue card was randomized among participants.

Participants were told that they would be performing two medical respiratory scenarios using the props provided. They were told to begin with the RSP, and where to locate the cue card. Participants were told not to remove the cue card from the protective plastic pocket, as ISS crewmembers are told, so that the cue card does not become unreadable or lost. Participants were also told that they would be timed and their errors would be recorded by the test conductors. Furthermore, they were asked to talk aloud while performing the procedure so that the test conductors knew when they might be confused or stuck. After performing both scenarios, participants were given a questionnaire. Following the questionnaire, the test conductors spent additional time explaining the purpose of the study, and asking the participants if they had any remaining suggestions.

Procedure completion time, errors, and subjective ratings were recorded. The last iteration of the cue card featured a schematic of the RSP, colors, borders, and simplification of the flow of information (Figure 23-5). Results showed that the average scenario completion time for the original cue card was 6 minutes and 59 seconds and 3 minutes and 50 seconds for the redesigned cue card. The time to complete the RSP procedure was improved by 55%, 3 minutes and 9 seconds, with the new design. In an emergency situation, 3 minutes significantly increases the probability of saving a life. In addition, participants showed the highest preference for this design.

Results

The results of these evaluations and the new design were presented to a focus group of astronauts, flight surgeons, medical trainers, and procedures personnel. The final cue card was approved for flight. The revised RSP cue card is currently onboard ISS.

In addition, as part of these evaluations, the following cue card design guidelines were developed:

- Provide a definite "start" and "stop" point
- Create a linear flow of information
- Add numbers to steps
- Add schematic(s) or picture(s) to cue card, but avoid too many pictures/too much detail

PCS Airlock: ECLSS O_2 Lo P Sply Vlv
AL O_2 Lo P Supply Vlv
cmd Open
Verify actual position OPEN.

RSP Setup

1. Deploy RSP.
2. Remove metal dustcap from regulator supply hose and connect to CHeCS O_2 supply hose. (**If CHeCS O_2 supply unavailable, attach PBAs or shuttle O_2 source).
3. Decide whether to use low flow mask, ambu bag, or intubate. (If intubating, attach patient valve to ET tube. Set RSP, BPM = 12, TV = 800).
4. Determine if additional treatment is required.

Conscious

O_2 to low flow mask
- BPM knob = dot
- Set regulator flow rate = 12 L/min (CAUTION: use WHITE indicator line).
- √Output by feeling for O_2 flow from regulator hosebarb
- Remove low flow mask from RSP lid pocket and attach O_2 tubing to regulator hosebarb.
- If low flow mask will be used for >15 min, disconnect autovent supply hose from regulator at quick disconnect (QD).

Unsconscious

O_2 to ambu bag
- Turn autovent BPM knob = dot
- Set regulator flow rate to 12 L/min (CAUTION: use WHITE Indicator line).
- √Output by feeling for O_2 flow from regulator hosebarb with hand
- Remove ambu bag from ALSP and attach ambu bag O_2 supply hose to regulator hosebarb.
- Give one breath every 5 s with ambu bag and mask (or remove mask and attach ambu bag to ET tube).
- If ambu bag will be used for >15 min, disconnect autovent supply hose from regulator at quick disconnect (QD).

Intubated

O_2 to ET tube
- For use only in intubated patient
- Set regulator flow rate = 0 L/min (CAUTION: use WHITE Indicator line).
- Set Autovent BPM = 12 initially
- Set Autovent tidal volume = 800 mL
- √For O_2 flow by observing movement in green indicator on top of patient valve and by feeling for O_2 flow
- Attach patient valve to ET tube.
- Secure O_2 line as needed.

Will patient be transported back to earth through shuttle?

Yes

Patient transported to earth
- Remove patient extension hose from RSP lid pocket and remove one heat and moisture exchanger (HME) from RSP.
- Attach top (small end) of HME to L-shaped end of extension hose.
- Quickly disconnect patient valve from ET tube, connect HME to ET tube, and connect extension hose to patient valve.
- Retrieve portable breathing apparatus (PBA).
- Obtain ISS manned systems extension O_2 line from node or airlock.
- Connect extension O_2 line to space shuttle O_2 source: Panel M069M/M032M.
- Switch O_2 supply from ISS CHeCS rack to PBA.
- Move patient to shuttle.
- Switch O_2 supply from portable O_2 bottle to shuttle O_2 source through extension line.
- Secure patient in shuttle for return to earth.
- Secure autovent, regulator, patient valve, and all flex lines near patient with velcro straps in RSP lid.

No

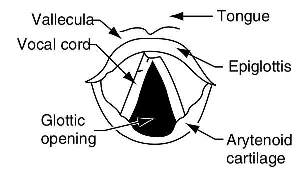
Patient NOT transported to earth
- If patient is to remain on autovent >15 min, insert HME between patient valve and ET tube.
- Complete patient treatment per ISS medical C/L or surgeon instructions.
- Use an alcohol pad to clean used equipment.
- Restow RSP.

Note

For detailed intubation procedures go to {Cardiopulmonary Resuscitation: CPR - TRACHEAL INTUBATION} (SODF: ISS MED: BASIC LIFE SUPPORT).

ALSP (red)

1. Unstow:
   Endotracheal (ET) tube with stylet (Airway-15)
   Xylocaine jelly (Airway-14)
   10 mL syringe (Airway-12)
   Laryngoscope (Airway-16)
   Ambu bag (ALSP-6)
   Stethoscope (ALSP-1)
2. Insert 10 mL Syringe into one-way valve of ET tube and inflate cuff.
3. Remove 10 mL syringe to confirm cuff and valve integrity (cuff stays inflated).
4. Replace 10 mL syringe and deflate cuff.
5. Lubricate cuffed end of ET tube with xylocaine jelly.
6. Hyperventilate the patient for 30 s.
7. Open the patient's mouth with right hand.
8. Hold laryngoscope in left hand, and insert laryngoscope blade into the patient's mouth.
9. Advance laryngoscope blade into space between base of tongue and epiglottis.
10. Lift tongue with laryngoscope blade tip to expose the vocal cords.



11. Advance cuffed end of ET tube along right side of mouth, past vocal chords and into trachea until entire cuff is about 1.3 cm or (0.5 in.) below vocal cords.
12. Inflate ET tube cuff with air from 10 mL syringe, remove stylet, and hold ET tube firmly in place.
13. Attach ambu bag to ET tube and give the patient two breaths.
14. Check for breath sounds in both lungs, and if necessary, reposition ET tube until breath sounds confirmed.
15. If intubation and ET tube repositioning unsuccessful, remove ET tube, hyperventilate the patient for 30 s and reattempt procedure starting at step 5.
16. If successful, tape ET tube securely in place.
17. Remove ambu bag and attach RSP patient valve to ET tube.
18. Deliver oxygen through RSP ventilator (BPM = 12, TV = 800, Reg = 12 L/min).

FIGURE 23-4 Original respiratory support pack cue card. BPM, beats per minute; CHeCS, Crew Health Care System; ALSP, advanced life support pack; ISS, International Space Station.

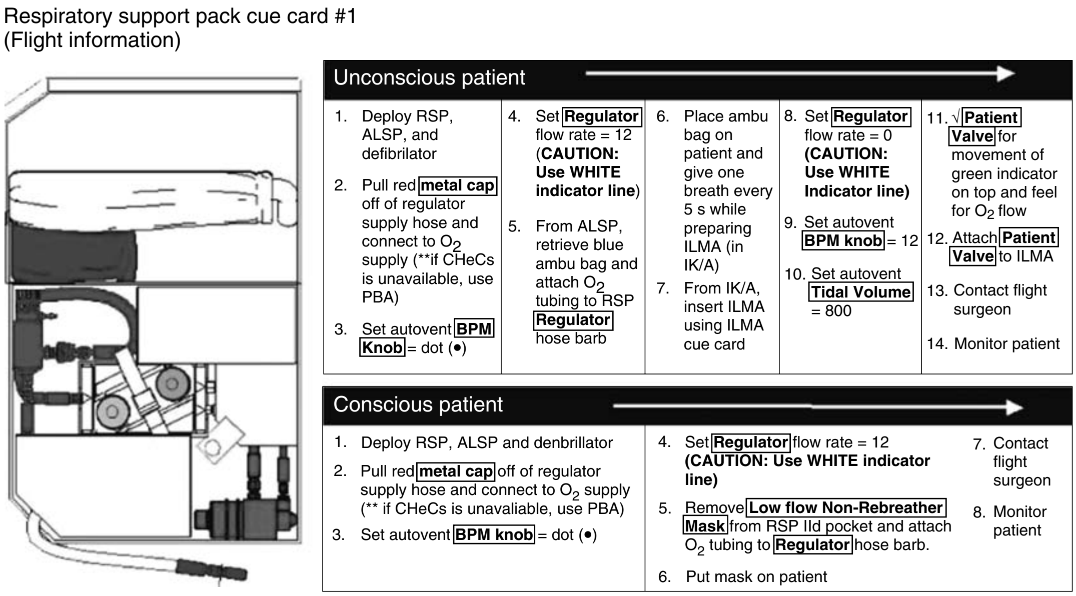


FIGURE 23-5 Revised respiratory support pack cue card onboard the International Space Station. ALSP, advanced life support pack; ILMA, intubating laryngeal mask airway; BPM, beats per minute; IK/A, intubating kit/airway; CHeCS, Crew Health Care System; PBA, portable breathing apparatus.

- Use color where feasible for identification, but do not overuse color (e.g., for decoration)
- Highlight important words with the use of bold, underlined, or bordered text

Conclusion

Human-system interfaces are very crucial for the overall system performance. If the interfaces are designed properly, the users can do their tasks safely and efficiently, with minimal errors, training, and stress. If an iterative design process is used in the development of user interfaces, the outcome will be effective and efficient. The key to optimum design is to thoroughly identify the user requirements and needs up front, design the user interface for accommodating these requirements, and test and retest the design to verify and validate that the correct requirements are used and are met.

Crew Resource Management

Overview

CRM is formal training for aircrew designed to improve crew coordination, communication, and ultimately safety in aviation. It has been defined as the effective use of all available resources: human resources, hardware, and information in order to achieve a safe flight (30,31). Typically, modern CRM programs include training in teamwork skills, leadership, decision-making, and communication, as well as primary education in human factors. Originally termed *Cockpit* Resources Management, the current *Crew* Resource Management more accurately reflects the inclusion of non–pilot aircrew and other personnel whose actions impact on flight safety. In the United States, the Federal Aviation Administration (FAA) requires CRM training for all commercial carriers; guidelines for training as well as its design and implementation are currently described in FAA Advisory Circular 120-51E (32). CRM has become a globally recognized practice to improve aviation safety. Outside the United States, similar requirements and guidelines are provided by other flight safety authorities, such as the International Civil Aviation Authority (ICAO) (31) and the Civil Aviation Authority (CAA) in the United Kingdom (33), as well as numerous military commands around the world.

Despite a common perception that the objective of CRM is "better teamwork," the true purpose of these programs is to improve flight safety through appropriate management of human resources. Properly executed training programs go well beyond the basic concept of "team training," and are integrated with more conventional technical skills training, often using flight simulation as a key mode of delivery. Continual reinforcement of CRM skills is an essential element of ongoing airline or squadron line operations. In recent years, CRM has been extended to include ongoing assessments of threats to safety by aircrew and the management of errors that are, to some extent, inevitable in technologically complex operational environments; a concept recently termed *Threat and Error Management*.

In TEM, crews go beyond the rote application of learned CRM skills and focus on risks and threats that present themselves through the flight. Bad weather, for example, may be identified *en route*, with discussion of the safety implications that it presents, and a crew-level analysis of the best course of action to minimize the risk presented. TEM also involves the idea that errors and mistakes by crewmembers will occur in any flight, and a nonblame approach to error is emphasized. By shifting the focus from blame to safety, the error is dealt with as any other threat to safety, and best course of action is discussed in an open atmosphere to determine the most appropriate response to the new situation.

Illustrative Description

Origins

Formal CRM training in commercial aviation appeared at the end of the 1970s, a decade in which human error and human factors were frequently identified as contributing causal factors in a number of high–profile aviation disasters. Among the most often cited accidents is that of Eastern Airlines Flight 401. Flight 401 was a Lockheed L-1011 passenger jet traveling from New York to Miami on December 29, 1972. Problems arose while the aircraft was on final approach into Miami International Airport when a gear down-and-locked confirmation indicator light failed to illuminate. The crew elected to abort the landing, climbed to holding altitude, and engaged the autopilot. As they tried to identify the source of the problem, the autopilot inadvertently became disengaged and the aircraft lost altitude. The crew remained unaware of the dropping altitude, and the aircraft impacted the everglades swamp at 227 knots. Of the 176 people onboard, 101 died on impact, and 2 more in the days that followed. Investigation by the NTSB concluded that during the final few minutes of flight, the crew failed to monitor the flight instruments and aircraft status during this critical period of low-altitude flight. Examination of the wreckage found that the gear was actually down-and-locked, and the indicator light failure was due to a burned-out bulb (34).

Another highly significant accident was the runway collision of a Royal Dutch Airlines (KLM) 747 and a Pan American Airlines (Pan Am) 747 on the island of Tenerife on March 27, 1977. With 583 people killed, this accident remains the single worst accident in aviation history. These aircraft were among several that had been diverted to a secondary airport on Tenerife when a terrorist bomb temporarily closed Gran Canaria International, the main airport for that island. This diversion, combined with long duty hours and bad weather, set the stage for confusion during taxiing and takeoff later that day when Gran Canaria reopened. The collision occurred in the fog as the KLM aircraft attempted takeoff and as the Pan Am jet taxied along the same runway. Seeing the Pan Am aircraft at the last minute, the KLM pilot attempted to climb over the taxiing aircraft but failed to do so, shearing off the top of the Pan Am jet and causing both aircraft to burst into flames. Failure to obtain proper clearance, the cumulative effects of long flight times and delays, command style, confusion over flight and ground control, and nonstandard radio communication have all been identified as contributing factors in this accident.

Following these and other accidents, NASA convened a workshop in 1979 to address aviation safety in general, and crew factors specifically (35). Failure in communication, problems of task fixation, loss of situational awareness, and errors in decision making were all identified as recurrent and critical issues in numerous accidents in the preceding years. Data suggested that up to 70% of accidents were due to crew issues, as opposed to mechanical, maintenance, or weather (36). Formal training in crew management was proposed as a solution, and the term *cockpit resource management* was born.

On the basis of the models borrowed from management consulting, early CRM programs strived for both task-oriented and team-oriented approaches to crew management. In the early 1980s, United Airlines became the first U.S. carrier to create a formal CRM program, combining theoretic foundations with simulator-based training (37). Many of the fundamentals of CRM were established in this early program, including the establishment of expectancies for crewmembers to raise safety concerns whenever present, providing clear guidelines for decision making, and defining rational approaches to conflict resolution. It is important to note that while CRM represented a training solution for all pilots, many pilots would have already exhibited this optimal style of cockpit management, and that such a style would have been described as superior *airmanship* or excellence in *captaincy* in the days before formal CRM. In some ways, CRM can be thought of as taking that mix of skills already present in good pilots, and packaging it in a training program so that all aircrew can achieve that same level of safety and crew performance on the flight deck.

Current Standards in Crew Resource Management Training

CRM training has gone through a number of significant changes since first developed. One important advance has been the shift from a cockpit-centered training model to one that includes cabin crew and other personnel whose actions have the potential to impact upon flight safety. This change has been reflected in the aforementioned shift of CRM from *cockpit* to *crew* resource management. Well-trained crews ensure the timely flow of critical information to and from the cockpit and create an environment where safety exists as a super ordinate goal for all crewmembers. The concept of shared mental models has emerged as one of the key elements in maximizing crew coordination (38). Helmreich has described at least six discrete generations of CRM over the last 25 years, each with fundamental advances in both theory and application over its predecessor. Current well-designed CRM programs focus on continual reassessment of threats to safety. This approach accepts the inevitability of occasional crew errors and stresses the need to trap and manage those errors when they occur. This approach has been termed *threat and error management* and represents the state of the art in CRM currently (39).

As mentioned previously, FAA Advisory Circular 120-51E describes the current FAA requirements for CRM training. This document divides required CRM components into two broad areas, (a) communication process/decision behavior and (b) team building and maintenance. The first topic area includes briefings, assertion, self-critique, conflict resolution, communication, and decision making. The second topic area includes leadership, followership, concern for task, interpersonal skills and group climate, workload management, situation awareness, individual factors, and stress reduction (32). These guidelines also describe key aspects of successful programs, including the need for initial indoctrination training, subsequent recurrent training, and reinforcement throughout routine line operations at all levels. While the FAA grants authority for actual course design to individual airlines (in order to customize needs to specific carrier operations), all programs must meet the guidelines as set out in the advisory circular. Two recent reviews by Salas et al. from the University of Central Florida identified considerable variability between carriers in terms of how the requirements laid out in AC 120-51e are operationalized at various airlines (40,41). This raises the question of whether the current approach to implementing CRM is optimal. Efforts to export CRM programs from one airline to another, and from U.S. carriers to non–U.S. carriers, have proved problematic due to differences in organizational culture and specific flight operations.

Furthermore, attempts to export specific CRM training programs from U.S. carriers to non–U.S. carriers have met with difficulty. Fundamental elements of CRM, such as encouraging junior officers to voice their concerns to more senior captains involve issues such as challenging authority and countering command hierarchies. Such practices may seem simple and appropriate in typical western and northern European cultures, but are more complex in those countries that typically have steep authority gradients. Conversely, many cultures are typically more rule-adherent than western cultures. Crews from such backgrounds operate with different behavioral ground rules, and SOPs may be expected to be followed more closely than in the West. Helmreich has written extensively on differences in organizational culture and national culture, and how these differences affect CRM training. The lesson appears to be that training programs need to be tailored to the specific environment of each airline, and that the national norms of social structure and communication need to be addressed in curriculum design (41,42).

Future Challenges

A series of studies conducted in the 1990s suggested significant individual variation in pilots' responses to CRM training programs. Earlier it was suggested that some pilots might naturally exemplify superior CRM skills, even before exposure to training. The opposite is also likely true; some pilots may not be well suited to the concepts taught in CRM training. Helmreich has identified two subsets of individuals, one subset with high-achievement needs but with high levels of interpersonal hostility, and another subset with overall low-achievement motivation. Both sets of individuals have been identified as potentially problematic when it comes to CRM skills and training receptivity*. Pilots with high hostility were found to reject CRM concepts as measured in post–course attitude questionnaires (43), presumably because skills taught were incongruent with their personal management style. In flight simulation studies, crews with captains from both groups (low motivation and high hostility) performed more poorly than pilots with high motivation and good interpersonal skills (44,45). These studies are often cited as justification for the use of psychological testing in the selection of both pilots and astronauts. They also suggest that while CRM training may be an effective tool to improve flight safety, individual factors cannot be ignored, and the degree to which CRM can compensate for poor natural leadership is not well understood.

Another issue of some controversy is the degree to which CRM has actually achieved its goal of improving flight safety. Such research has proved challenging, and definitive proof of effectiveness has remained elusive. Salas et al. have conducted several reviews over the last few years in an attempt to determine the degree of supporting evidence for the effectiveness of CRM. The evidence for positive receptivity among trainees is strong, and there is also good evidence that attitudes following training show positive shifts in desired directions. Studies demonstrating actual behavior change are difficult to conduct, and evidence of this finding is much more difficult to gather. Actual impact on flight safety has proved exceedingly difficult to measure. CRM has been implemented over the last 25 years in concert with a myriad of other safety initiatives, including improved weather radar, wind shear detection systems, improved autopilot and automation, and so on, making it difficult to attribute improvements in safety to any one factor.

It is probably safe to say, however, that there is significant face validity to the concept of CRM, and anecdotal reports of its success are relatively commonplace. One of the most commonly cited examples of such evidence was the flight of United Airlines (UAL) Flight 232. This aircraft, a fully laden DC-10, experienced a catastrophic hydraulic failure and loss of one of three engines *en route* from Denver to Chicago on the afternoon of July 19, 1989. By any account, the resulting complete loss of hydraulics rendered the aircraft unmaneuverable, and expectations were that the aircraft would inevitably crash and all personnel would perish. In what remains an outstanding display of piloting ability and ingenuity, Captain Al Haynes and his crew (including a DC-10 instructor pilot who was deadheading as a passenger) managed to devise a means of controlling the aircraft using differential thrust with the two remaining engines. Despite all expectations, the crew managed to land the aircraft at Sioux City, Iowa, losing control only in the final feet of decent. Although the aircraft cart wheeled down the runway and burst into flames, many passengers and crew survived. Haynes has long attributed his ability to fly the damaged aircraft to skills he acquired in United Airline's CRM training program, and this crash landing and the survival of more than half the passengers onboard remains one of the great success stories of CRM to date.

Conclusion

Few people with firsthand experience in aviation consider CRM training to be either completely ineffective or a

*Helmreich describes the subset of individuals with high-achievement needs but also high levels of interpersonal hostility as the *Wrong Stuff*, and the other subset of individuals with low-task motivation as *No Stuff*. This somewhat tongue-in-cheek description is in contrast to the concept of the *Right Stuff* described in Tom Wolfe's account of the early test pilots and astronauts (41) universal remedy for all matters related to flight safety. There is, however, a general consensus that CRM is an integral component of a comprehensive approach to improving safe flight operations. As aviation technology changes and as computerization and automation play ever increasing and changing roles in aircraft operation, CRM will need to develop to address the challenges and changes in role experienced by aircrew.

Unmanned Aircraft Systems

Overview

This is an exciting time for those directly involved or supporting civil and military aerospace operations given the advent of an entirely new aerospace occupation, the UAS crewmember (see also Chapter 27). For aerospace medicine practitioners, there are both significant challenges and opportunities in addressing the immediate and forecasted future aeromedical needs for this novel and rapidly growing career field. While technology can simplify the operation of a single UAS, it is also increasing the span of control of individual operators, and in the end is creating a diversity of task environments, some of which are more complex than those seen in traditional aviation. The overall trend then is for technology to enhance rather than diminish the role of the human operator in "unmanned" aviation. As such, attending to human performance issues is critical for the success of current and future UAS crewmembers. No different from traditional aircrew, it is the responsibility of aerospace medicine practitioners to function as advocates for UAS crewmembers by using their specialized knowledge to help optimize human performance. Consistent with the fundamental occupational medicine precept of the necessity of the physician workplace visit, it is important for aerospace medicine practitioners to directly observe and participate in UAS operations because: (i) the diversity of Ground Control Station (GCS) designs prohibits generalizations about UAS task environments based on knowledge gained from an individual UAS, and (ii) current aerospace medicine practice is based largely on a subset of the spectrum of existing and potential UAS task environments (Figure 23-6).

Perhaps the sole consistency across the spectrum of UAS is the fact that the crew and the aircraft are no longer necessarily co-located. From an occupational medicine perspective, this makes UAS the engineering control solution for such traditional aerospace medical hazards as hypobarics, hypoxia, acceleration, vibration, thermal stress, and those forms of spatial disorientation associated with acceleration. Nevertheless, UAS historically have suffered mishap rates one to two orders of magnitude greater than those of manned aviation with various studies attributing 17% to 69% of the mishaps to human factors (46). Although aerospace medicine human factors remain pertinent in UAS, there are differences in the relative importance of specific human factors concerns for unmanned versus manned aviation (Table 23-2). Because optimum human performance remains a necessary, albeit not sufficient, condition for the safe and efficient operation of UAS, and appreciating the very heterogeneous nature of UAS task environments, aerospace medicine practitioners should become proficient in utilizing the Human Systems Integration (HSI) model of human performance to consistently and systematically assess the underlying determinants of crewmember performance in individual UAS (Figure 23-7). Past applications of this model have shown that UAS crewmember performance

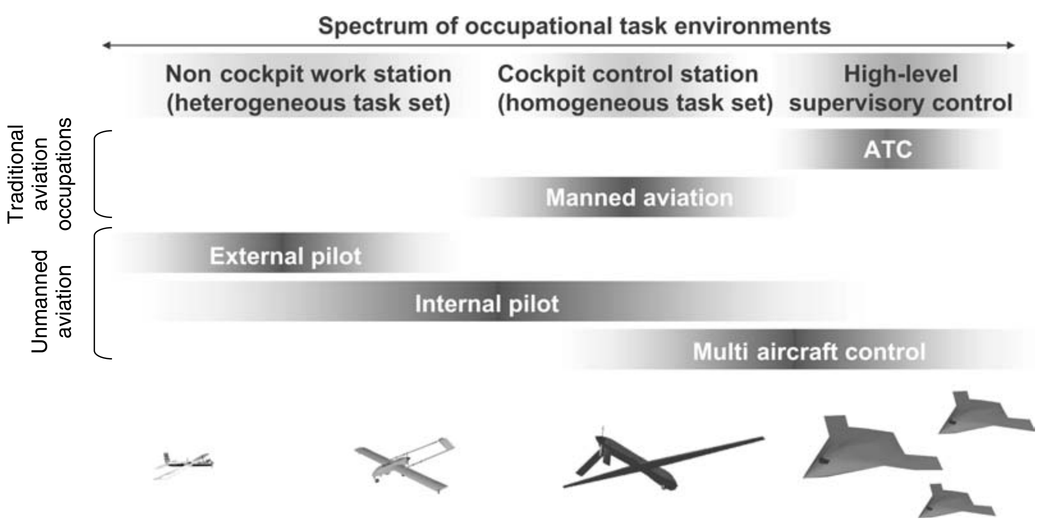


FIGURE 23-6 An occupational medicine perspective of the diversity of task environments for unmanned aircraft system pilots (external, internal, and multi-aircraft control pilots) relative to traditional manned aviation pilots and air traffic control (ATC) specialists. External pilots control unmanned aircraft through direct visual contact with the aircraft. Internal pilots control unmanned aircraft using information provided through control station displays. Of note, manned aviation and ATC task environments are inclusive of a relatively homogenous subset of UAS task environments. Therefore, caution is required in drawing analogies between manned and unmanned aviation.

TABLE 23-2

Comparison of Aerospace Medicine Human Factors Concerns for Manned Aircraft (MA) versus Unmanned Aircraft System (UAS) Crewmember Performance Using Human Factors Analysis and Classification System (HFACS) Categories of Preconditions

Factors	*MA*	*UAS*[a]
Physical environment	+	+
Vision restricted (clouds, ice, etc.)	+	+
Noise and vibration	+	±
Windblast	+	0
Thermal stress	+	±
Maneuvering forces	+	0
Technologic environment	+	+
Seating and restraints	+	0
Instrumentation	+	+
Visibility restrictions (e.g., FOV)	±	+
Controls and switches	+	+
Automation	+	+
Personal equipment	+	0
Cognitive	+	+
Vigilance and attention management	+	+
Cognitive task oversaturation	+	+
Confusion	+	+
Motion sickness	+	±
Hypoxia and hypobarics	+	0
Visual adaptation	+	±
Physical task oversaturation	+	+
Perceptual factors	+	+
Illusion—kinesthetic	+	0
Illusion—vestibular	+	0
Illusion—visual	+	+
Misperception of operational conditions	+	+
Misinterpreted/misread instrument	+	+
Spatial disorientation	+	+
Temporal distortion	+	+
Crew coordination and communication	+	+
Distributed/virtual crew	0	±
Negative transfer	+	+
Distraction	+	+
Geographic misorientation (lost)	+	+
Checklist interference	+	+
Psycho-behavioral	+	+
Personality style or disorder	+	+
Emotional state	+	+
Overconfidence	+	+
Complacency	+	+
Motivation	+	+
Burnout	+	+
Adverse physiological states	+	+
Effects of G forces	±	0
Prescribed drugs	+	+
Sudden incapacitation	+	+
Preexisting illness or injury	+	+
Physical fatigue	+	+
Mental fatigue	+	+
Circadian desynchrony	+	+
Shift changeovers	0	±
Self-imposed stress	+	+
Physical fitness	+	+
Alcohol	+	+
Drugs, supplements, or self-medication	+	+
Inadequate rest	+	+
Unreported disqualifying medical condition	+	+
Miscellaneous		
Multiaircraft control	0	±
Control and feedback latency	0	+
Standardized cockpit design and controls	+	0
Manual control of aircraft	+	±
Standardized crew qualifications	+	0
"Shared fate" with aircraft	+	0

+ = usually applicable, ± = possibly applicable, 0 = not applicable.
[a]If a UAS is operated from another airborne platform, all MA performance concerns would also apply. FOV, field of view.
Federal Aviation Regulation. Sec. 135.267. http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr;sid=f4637c62296f8bd572410435a95a1bc2;rgn=div8;view=text;node=14%3A2.0.1.4.23.6.11.4;idno=14;cc=ecfr, (accessed 17 July 2007).

is impacted by issues involving the HSI domains of human factors engineering; personnel; training; manpower; environment, safety, and occupational health (ESOH); and habitability (47).

Illustrative Description

Domains: Personnel and Training

Currently, there are no uniform standards across the U.S. military services for UAS crewmember selection, training, and certification (48), nor are there formal civil standards for the training and certification of UAS pilots (49). Although various organizations are developing recommendations for standards (American Society for Testing and Materials subcommittee F-38.03; NASA's Access 5 program (inactive); Radio Technical Commission for Aeronautics (RTCA) incorporated special committee 203; and SAE International's G-10 Aerospace Behavioral Engineering Technology Committee), there currently exists only a small number of well-designed studies (50–52) addressing the necessary prerequisite knowledge, skills, and abilities for UAS pilots and conflicting findings and expert opinion regarding the value of prior manned aircraft flying experience (49,50,52,53). There are also few studies (51,54) addressing medical certification standards for UAS pilots

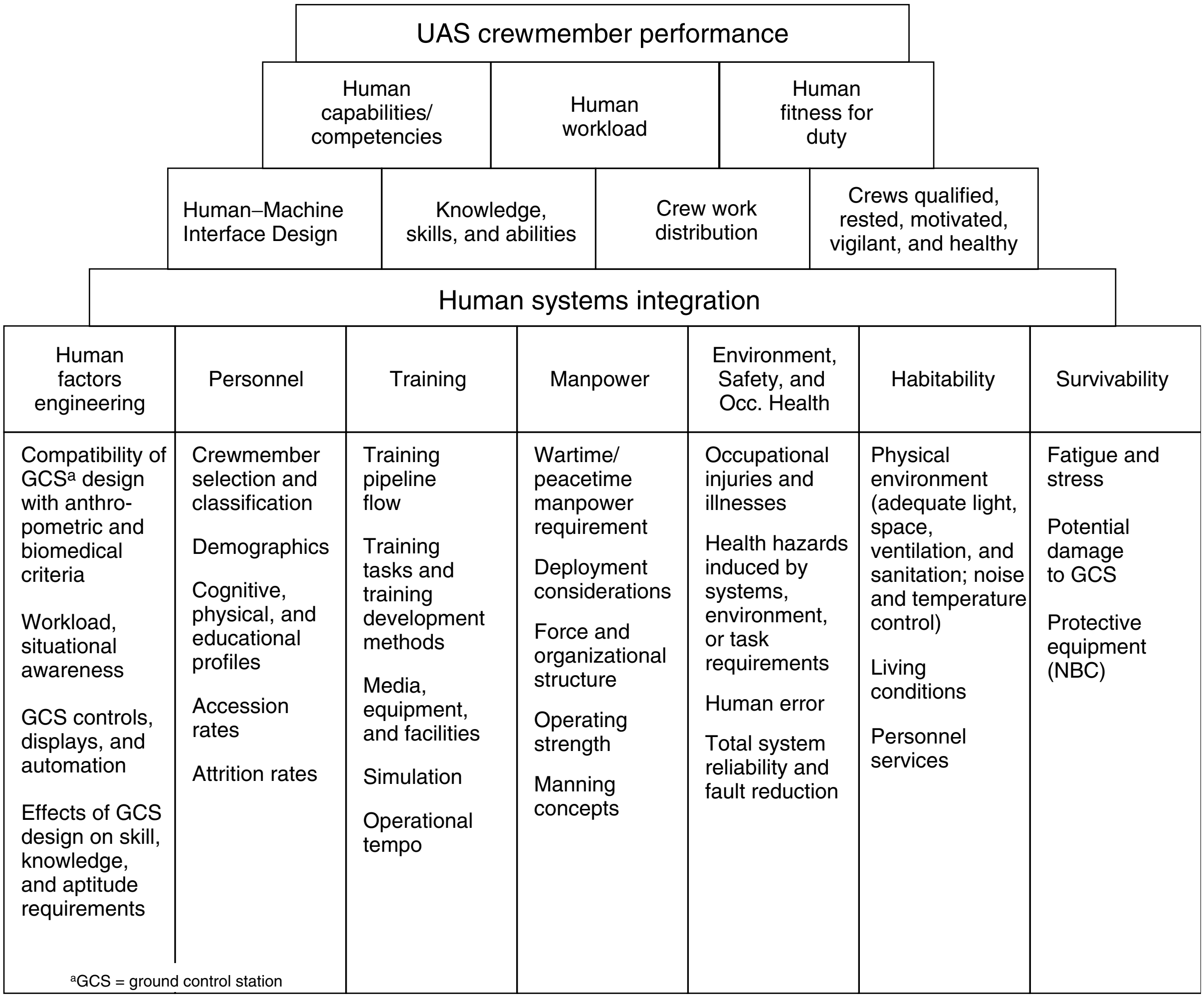


FIGURE 23-7 Process model for obtaining unmanned aircraft system (UAS) crewmember performance from the domains of human systems integration (HSI) with UAS-relevant examples of HSI elements/areas of concern for each domain.GCS, ground control station, NBC, nuclear, biological, and chemical. (Adapted from Tvaryanas AP. Human systems integration in remotely piloted aircraft operations. *Aviat Space Environ Med* 2006;77(12):1278–1282.)

based on an empirical analysis of the UAS task environment, and even less data to guide liberalizing current standards in order to address aeromedical accommodation (49). One of the chief barriers in addressing UAS personnel selection, training, and certification issues continues to be the heterogeneity in UAS control station design, and therefore occupational task environments, leading to similar job titles encompassing divergent skill and aptitude requirements based on UAS (Figure 23-8). Some progress has been made in defining a generic, high-level workflow with associated knowledge, skill, and aptitude requirements for USAF medium- and high-altitude endurance UAS (Figure 23-9), but this represents only a fraction of the total UAS spectrum.

Domain: Human Factors Engineering

The UAS crew is unique compared to traditional aircrew because their task environment is the GCS rather than the cockpit. They often lack peripheral visual, auditory, and somatosensory cueing and are therefore relatively sensory deprived. They are nearly entirely dependent on focal vision in order to obtain information on vehicle state through either automation and displays or direct visual contact. This effectively limits the crew to the use of the central 30 degree of their visual field and requires them to process information using a neurosensory pathway not naturally adapted to providing primary spatial orientation cues (i.e., focal vision). The effect of this sensory deprivation has not been well researched and little is known where UAS crewmembers direct their attentional focus or what information they use. For instance, a study (55) of visual scan patterns using a MQ-1 Predator head-up display (HUD) revealed nonstandard instrument scan patterns with no adjustment to compensate for the lack of auditory or haptic cueing of engine performance. Additionally, a review of UAS mishaps (46) found that human–machine interface design and crewmember attentional factors were frequent causes of crew-related errors. While offloading perceptual workload to nonvisual channels seems an intuitive solution, preliminary

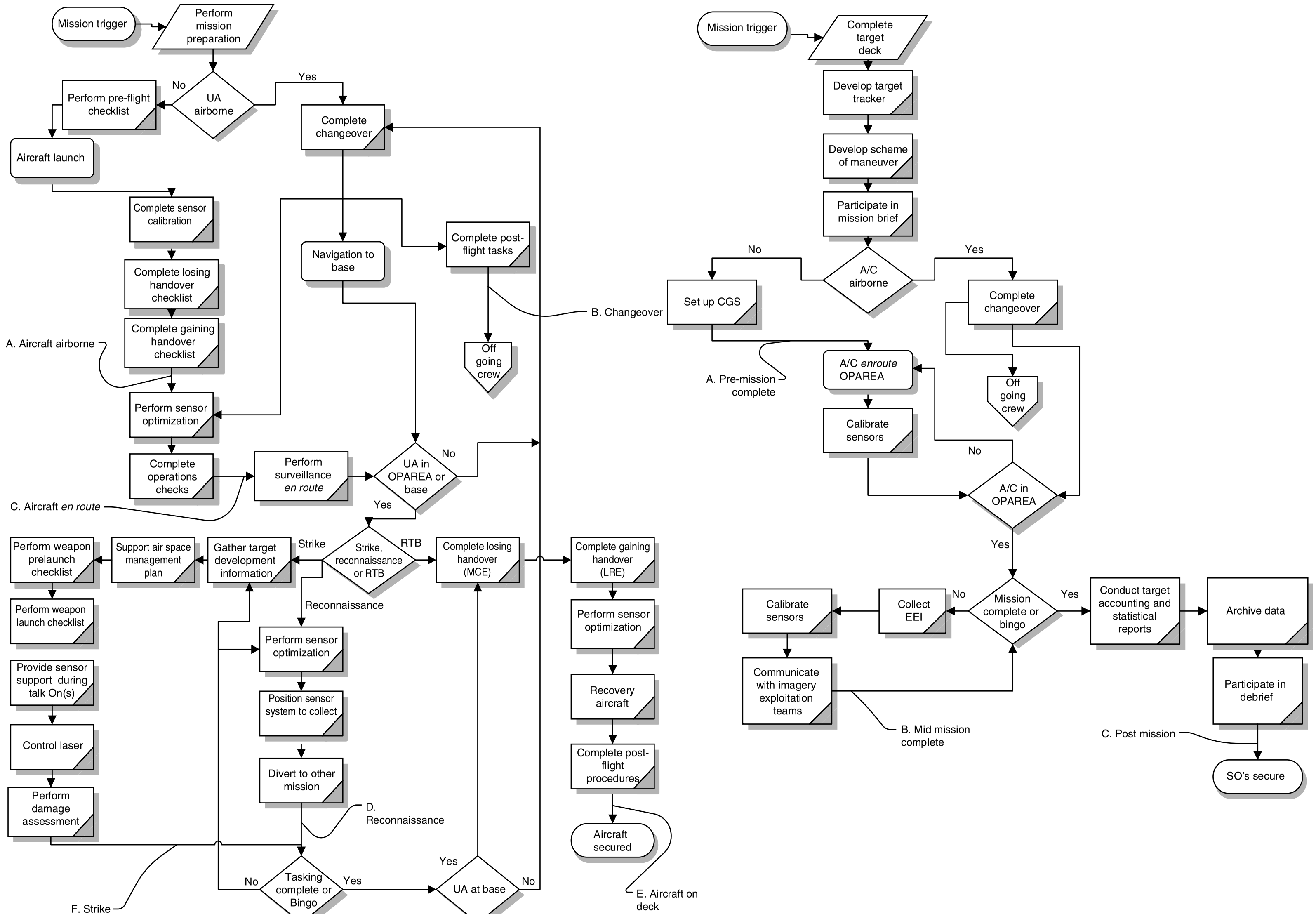


FIGURE 23-8 Workflow breakdowns for the sensor operator (SO) crewmember in the MQ-1 Predator unmanned aircraft system (UAS) (A) versus the RQ-4 Global Hawk UAS (B). Despite the same job title, the job content is very different based on UAS, making it impracticable to consider these equivalent positions for the purposes of selection and training. UA, unmanned aircraft; CGS, California Geological Survey; OPAREA, operating area; RTB, return to base; MCE, mission control element; LRE, launch and recovery element; EEI, essential element of information.

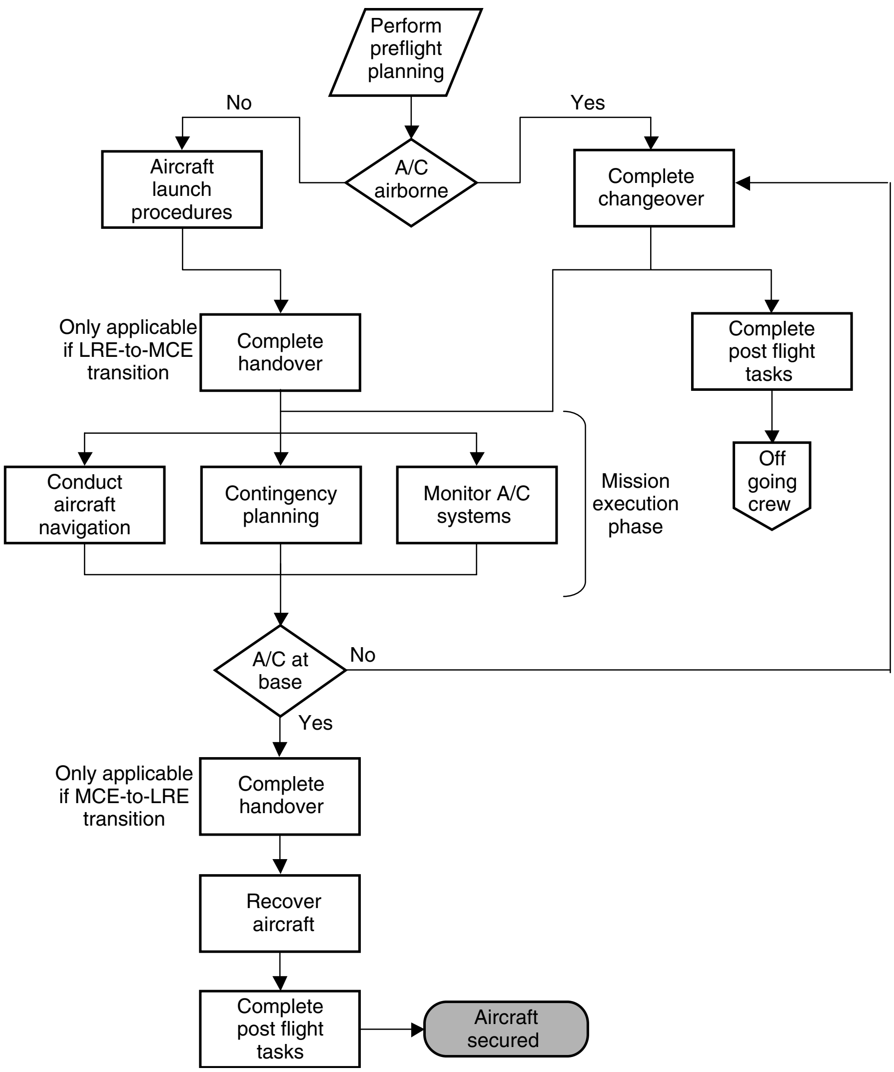


FIGURE 23-9 Payload independent, core UAS pilot workflow based on synthesis of MQ-1 Predator, MQ-9 Reaper, and RQ-4 Global Hawk task analyses. LRE, launch and recovery element; MCE, mission control element.

work with multimodal displays has yielded mixed results and still needs to be further studied (56).

Advances in automation are decreasing the need for UAS pilots to have traditional pilot skills and instead emphasize monitoring and collaborative decision-making skills. However, the role of passive monitor makes maintaining a constant level of alertness exceedingly difficult and predisposes to "hazardous states of awareness" (57). This was demonstrated in a study (58) of USAF UAS crewmembers that found high levels of subjective boredom and significant decrements in vigilance performance over the course of a single 8-hour shift. Likewise, a study (59) of Army UAS pilots demonstrated degraded target detection and recognition performance as well as longer reaction times during nocturnal operations involving long flights. Although one of the best ways to overcome these effects is work breaks, there is concern for an acute decrement in crew situational awareness when control is transferred to another crew not currently involved in the mission. For example, the aforementioned Army UAS pilots preferred longer over shorter rotations because of the perception that longer rotations allowed for better situational awareness of the tactical environment (59). This is consistent with findings from other occupational domains such as ATC (60,61) and even medicine, where patient transfers or handoffs were found to be one of the largest sources of medical errors (60,61).

Perhaps most unique of UAS is multi-aircraft control (MAC) where a crew controls more than one aircraft. For example, the recently fielded MQ-1 Predator MAC GCS provides the capability for one pilot and four sensor operators (SOs) to control a maximum of four aircraft. The impact of transforming the role of the UAS pilot from that of a single aircraft operator to a multiple systems manager on knowledge, skill, and aptitude requirements is currently unknown. An FAA-sponsored review of the UAS human factors literature (56) concluded there is only limited research suggesting one person may control more than one unmanned aircraft under relatively idealized conditions to include closely coordinated and correlated activities, a stable environment, and reliable automation. Other research (62) has demonstrated performance controlling even a single unmanned aircraft is significantly degraded when heavy demands are imposed by payload operations. This would suggest that the ability of a pilot to attend to multiple aircraft might be severely compromised under nonidealized conditions, especially if an aircraft is malfunctioning or damaged. MAC also introduces new considerations for aerospace medicine practitioners. First, the risk for impaired pilot performance must now be weighed against the potential impact on multiple missions rather than a single mission. Second, MAC allows pilots to delegate limited aircraft control to "nonpilot" crewmembers, thereby causing their duties to encroach on traditional pilot tasks. Finally, there is no data to suggest the necessity or method for adjusting current hours-of-service rules for MAC operations.

Domains: Environment Safety and Occupational Health, Survivability, and Manpower

The USAF's strategic vision for UAS suggests "the absence of onboard aircrew mitigates the historic limitations of aircrew fatigue" (63) in UAS operations. However, the introduction of long-endurance UAS has necessitated the implementation of shift work for crewmembers in order to provide the necessary around-the-clock staffing of GCS. Serious public health concerns have been raised regarding the association between the documented effects of shift work and resulting degraded work performance with accompanying increased risk for errors and accidents. These concerns were validated by a recent study (64), which found higher reported fatigue levels among USAF UAS crewmembers as compared to traditional aircrew. Despite the potential for fatigue to be highly prevalent in UAS operations, only limited research has been conducted on the effects of fatigue on UAS crewmember error or its impact on operational efficiency. A simulation modeling study (65) analyzing the effects of fatigue, crew size, and rotation schedule on Army UAS crew workload and performance predicted almost three times as many mishaps would occur when a crew was fatigued as compared to rested. Although the results of the former study have not been operationally validated, an observational field study (58) of USAF UAS crewmembers involved in rotational shift work noted decrements in mood, cognitive and piloting performance, and alertness associated with the acute fatigue of a single shift. This same study also found no association between hours-of-service rules for flying and reported acute or chronic fatigue.

Walters et al. notes operational requirements for UAS crewmembers "may include extended duty days, reduced crew size, and varying shift schedules," which are "likely to reduce operator effectiveness because of fatigue" (65). Restated from an HSI perspective, UAS crewmember performance is at risk because of multiple, potentially synergistic domain shortfalls involving manpower (e.g., extended duty days and reduced crew size), survivability (e.g., fatigue), and ESOH (e.g., reduced operator effectiveness). Additionally, the human factors engineering domain can be added to this mix when the design of the human–machine interface drives human error or inefficiency. Taken together, aerospace medicine practitioners should anticipate baseline-degraded performance in UAS crewmembers, which is an important consideration when recommending performance interventions or consulting on mishap investigations. Additionally, aerospace medicine practitioners should recognize that UAS crewmember work environments are potentially stressful, thereby increasing the likelihood for exacerbations of underlying clinical or psychological conditions. In particular, the adverse chronobiological effects of sustained rotational shift work are an important consideration when making aeromedical accommodation decisions.

Conclusion

This section introduced aerospace medicine practitioners to some of the HSI domain highlights underlying UAS crewmember performance. Although it is not reasonable to expect aerospace medicine practitioners to be experts in all these issues, they need to have a working knowledge of the main issues in order to fully understand the task environment and human performance challenges. This is of immediate relevance because current military aerospace medicine practitioners can be expected to make aeromedical dispositions on UAS crewmembers, participate in UAS-focused aeromedical education and training programs, advise UAS squadron leadership on crew performance issues, and provide human factors consultation as members of UAS mishap investigation teams. Additionally, it is not unreasonable to expect that civil aeromedical examiners will be seeing UAS crewmembers in their clinical practices in the near future.

SUMMARY

In summary, as stated by Chapanis (66), human factors engineering is the application of human factors to the design of systems, machines, tools, tasks, and environments for safe effective and comfortable human use. Ultimate objectives of human factors include the following:

- Facilitating operational efficiency (increase safety, minimize error)
- Achieving reliability, maintainability, and availability
- Providing user-centered design (improve work environment, reduce stress and fatigue, increase ease of use, comfort, user acceptance)
- Other considerations such as reducing loss of time and equipment

The key components of the human factors are *human capabilities* such as cognitive human performance and error, fatigue, anthropometry and biomechanics; *human-system interfaces* such as information transfer (displays and controls), human–computer interactions, communications and tools, and *environmental factors* such as habitability/architecture, noise/vibration, illumination/color, and temperature/humidity. A multiple disciplinary team is needed in order to apply human factors with a systems approach. This team could comprise experts in disciplines such as psychology, industrial engineering, occupational and environmental medicine, applied physiology, anthropometry, industrial design, operations research, and statistics. This chapter provided a limited overview of selected human factors components with emphasis on aerospace medicine applications. Readers interested in a more in-depth study of human factors can refer to texts such as:

Design Applications

Norman's The Design of Everyday Things (67)

Human Factors

Sander's and McCormick's Human Factors in Engineering and Design (28)

Nielson's Usability Engineering (29)

Ergonomics

Konz's Work Design: Industrial Ergonomics (68)

Psychology

Wicken's Engineering Psychology and Human Performance (69)

ACKNOWLEDGMENTS

Fatigue section supported by National Space Biomedical Research Institute through NASA NCC 9–58; AFOSR F49620-95-1-0388 and F-49620-00-1-0266; and NIH NR004281 and NIH RR00040.

REFERENCES

Introduction

1. Beaty D. *Naked pilot: the human factor in aircraft accidents*, 2nd ed. Ramsbury: The Crowood Press, 1995.
2. Human Factors and Ergonomic Society. *About HFES*. www.hfes.org/web/AboutHFES/about.html, (accessed 11 July 2007).
3. Kohn L, Corrigan J, Donaldson M, eds. *To err is human: building a safer health system*. Washington, DC: National Academy Press, 1999.
4. Food and Drug Administration. *Why is human factors engineering important for medical devices?* www.fda.gov/cdrh/humanfactors/important.html, (accessed 16 April 2004).
5. Stone R, McCloy R. Ergonomics in medicine and surgery. *Biomed J* 2004;328:1115–1118.
6. Food and Drug Administration. *FDA issues bar code regulation*. www.fda. gov/oc/initiatives/barcode-sadr/fs-barcode.html, (accessed 12 July 2007).

Fatigue

7. Durmer JS, Dinges DF. Neurocognitive consequences of sleep deprivation. *Semin Neurol* 2005;25:117–129.
8. Mallis MM, Banks S, Dinges DF. Sleep and circadian control of neurobehavioral function. In: Parasuraman R, Rizzo M, eds. *Neuroergonomics: the brain at work*. Oxford: Oxford University Press, 2007:207–220.
9. Van Dongen HPA, Maislin G, Mullington JM, et al. The cumulative cost of additional wakefulness: dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep* 2003;20:117–126.
10. *Federal aviation regulation*. Sec. 135.267. http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr;sid=f4637c62296f8bd572410435a95a1bc2;rgn=div8;view=text;node=14%3A2.0.1.4.23.6.11.4;idno=14;cc=ecfr, (accessed 17 July 2007).
11. *Federal aviation regulation*. Sec. 135.265. www.airweb.faa.gov/Regulatory_and_Guidance_Library%5CrgFAR.nsf/0/7416414817B0167C8625694A00702606?OpenDocument, (accessed 11 July 2007).
12. Cruz C, Della Rocco P, Hackworth C. Effects of quick rotating shift schedules on the health and adjustment of air traffic controllers. *Aviat Space Environ Med* 2000;71:400–407.
13. Mallis MM, DeRoshia CW. Circadian rhythms, sleep, and performance in space. *Aviat Space Environ Med* 2005;76:B94–B107.

Human Error

14. Reason J. *Human error*. Cambridge: Cambridge University Press, 1990.
15. Shappell SA, Wiegmann DA. U.S. naval aviation mishaps 1977–92: differences between single- and dual-piloted aircraft. *Aviat Space Environ Med* 1996;67(1):65–69.
16. Dismukes RK, Berman BA, Loukopoulos LD. *The limits of expertise: rethinking pilot error and the causes of airline accidents*. Aldershot: Ashgate, 2007.
17. Helmreich R, Klinect J, Merritt A. Line operations safety audit: LOSA data from US Airlines. *Presentation at the Second ICAO/IATA LOSA/TEM Conference*. Seattle: Boeing Training Center, 2004.
18. McDaniel MA, Einstein GO. *Prospective memory: an overview and synthesis of an emerging field*. Thousand Oaks: Sage, 2007.

Anthropometrics

19. Dempster WT. *Space requirements of the seated operator*. WADC Technical report 55–159. United States Air Force, Wright-Patterson AFB, Ohio: Wright Air Development Center, Air Research and Development Command, 1955.
20. Proctor RW, Van Zandt T. *Human factors in simple and complex systems*. Boston: Allyn and Bacon, 1994.
21. Gordon CC, Churchill T, Clauser CC, et al. *1987–1988 Anthropometric survey of U.S. Army personnel: summary statistics interim report*. (NATICK/TR-89/027, AD A209 600). Natick: US Army Natick Research, Development and Engineering Center, 1989.
22. Robinette KM, Daanen H, Paquet E. The CAESAR project: a 3-D surface anthropometry survey in second international conference on 3-D digital imaging and modeling, 1999. *IEEE Proceedings. IEEE Catalog Number: PR00062*. New Brunswick, 1999:380–386.
23. Meindl RS, Hudson JA, Zehner GF. *A multivariate anthropometric method for crew station design*. (Publication No.: AL-TR-1993-0054). Wright-Patterson AFB, Ohio: AL/CFHD, 1993.
24. Hendy KC. Air crew/cockpit compatibility: a multivariate problem seeking a multivariate solution. *AGARD Conference Proceedings No. 491*, 1990.
25. Albery CB, Bjorn VS, Schulz RB. A comparison of human and ejection seat test manikin static centers of gravity and moments of inertia. *SAFE J* 1998;28(1):17–31.
26. Buhrman JR, Andries MJ, Deren M. Risk factors in ejection seat design associated with upward ejection risk for a large occupant. *SAFE J* 1999;29(1):29–38.
27. Albery WB, Zehner GF, Hudson JA, et al. Degradation of pilot reach under G. *SAFE J* 2006;34(1):1–4.

User Interfaces

28. Sanders MS, McCormick EJ, et al. *Human factors in engineering and design*. New York: McGraw-Hill, 1987.
29. Nielson J. *Usability engineering*. Cambridge: Academic Press, 1993.

Crew Resource Management

30. Helmreich RL. Managing human error in aviation. *Sci Am* 1997;276: 62–67.
31. ICAO. *Human factors training manual*. International Civil Aviation Authority (ICAO), 1998.
32. FAA. *FAA advisory circular AC 120-51E Crew Resource Management*. Washington, DC: Federal Aviation Administration, 2004.
33. Safety Regulation Group. *CAP 737—Crew Resource Management (CRM) training guidance for flight crew, CRM Instructors (CRMIs)*

and CRM Instructor-Examiners (CRMIEs). West Sussex: Civil Aviation Authority, 2003.
34. NTSB. *Accident investigation report NTSB-AAR-73-14*. Washington, DC: National Transportation Safety Board, 1973.
35. Cooper JE, White MD, Lauber JK. *Resource management on the flight deck*. (NASA Conference Publication 2120, NTIS No. N80-22083). Moffat Field: National Aeronautics and Space Administration—Ames Research Center, 1979.
36. Helmreich RL, Foushee HC. Why Crew Resource Management? Empirical and theoretical bases of human factors training in aviation. In: Weiner EL, Kanki B, Helmreich RL, eds. *Cockpit Resource Management*. San Diego: Academic Press, 1993:3–45.
37. Wiener EL, Kanki BG, Helmreich RL. *Cockpit Resource Management*. San Diego: Academic Press,1993.
38. Orasanu J. Shared mental models and crew performance. *34th Annual Meeting of the Human Factors and Ergonomics Society*. Orlando, Florida: Human Factors and Ergonomics Society, 1990.
39. Klinect JR, Wilhelm John A, Helmreich RL. Threat and error management: data from line operations safety audits. In: Jensen R, Cox B, Callister J, et al. eds. *The tenth international symposium on aviation psychology*. Vol. 2. Columbus, Ohio: The Ohio State University, 1999:683–688.
40. Salas E, Fowlkes JE, Stout RJ, et al. Does CRM training improve teamwork skills in the cockpit? Two evaluation studies. *Hum Factors* 1999;41(2):326–343.
41. Salas E, Wilson KA, Burke CS, et al. Does Crew Resource Management training work? An update, an extension, and some critical needs. *Hum Factors* 2006;48(2):392–412.
42. Helmreich RL. Managing human error in aviation. *Sci Am* 1997;276:40–45.
43. Gregorich SE, Helmreich RL, Wilhelm JA, et al. Personality based clusters as predictors of aviator attitudes and performance. *Proceedings of the 5th international symposium on aviation psychology*. Vol. 2. Columbus: Ohio State University, 1989:686–691.
44. Helmreich RL, Wilhelm JA, Gregorich SE, et al. Preliminary results from the evaluation of cockpit resource management training: performance ratings of flight crews. *Aviat Space Environ Med* 1990;61(6):576–579.
45. Chidester TR, Helmreich RL, Gregorich SE, et al. Pilot personality and crew coordination: implications for training and selection. *Int J Aviat Psychol* 1991;1(1):25–44.

Unmanned Aircraft Systems

46. Tvaryanas AP, Thompson WT, Constable SH, et al. Human factors in remotely piloted aircraft operations: HFACS analysis of 221 mishaps over 10 years. *Aviat Space Environ Med* 2006;77(7):724–732.
47. Tvaryanas AP. Human systems integration in remotely piloted aircraft operations. *Aviat Space Environ Med* 2006;77:1278–1282.
48. Weeks JL. *Unmanned aerial vehicle operator qualifications*. Mesa: Air Force Research Laboratories, Mar 2000.Report No.: AFRL-HE-AZ-TR-2000-0002.
49. Williams KW. *Unmanned aircraft pilot medical and certification requirements*. Oklahoma City: Civil Aerospace Medical Institute, Federal Aviation Administration, Feb 2007. Report No.: DOT/FAA/AM-07/3.
50. Barnes MJ, Knapp BG, Tillman BW, et al. *Crew systems analysis of unmanned aerial vehicle (UAV) future job and tasking environments*. Aberdeen Proving Ground: Army Research Laboratory, Jan 2000. Report No.: ARL-TR-2081.
51. Biggerstaff S, Blower DJ, Portman CA, et al. *The development and initial validation of the unmanned aerial vehicle (UAV) external pilot selection system*. Pensacola: Naval Aerospace Medical Research Laboratory, Aug 1998. Report No.: NAMRL-1398.
52. Schreiber BT, Lyon DR, Martin EL, et al. *Impact of prior flight experience on learning Predator UAV operator skills*. Mesa: Air Force Research Laboratory, Feb 2002. Report No.: AFRL-HE-AZ-TR-2002-0026.
53. Hall EM, Tirre WC. *USAF air vehicle operator training requirements study*. Mesa: Air Force Research Laboratory, Feb 1998. Report No.: AFRL-HE-BR-SR-1998-0001.
54. Tvaryanas AP. *The development of empirically-based medical standards for large and weaponized unmanned aircraft system pilots*. Brooks City-Base: United States Air Force, 311th Human Systems Wing, Oct 2006. Report No.: HSW-PE-BR-TR-2006-0004.
55. Tvaryanas AP. Visual scan patterns during simulated control of an uninhabited aerial vehicle. *Aviat Space Environ Med* 2004;75(6):531–538.
56. McCarley JS, Wickens CD. *Human factors implications of UAVs in the national airspace*. Atlantic City: Federal Aviation Administration, Department of Transportation, Apr 2005. Report No.: AHFD-05-05/FAA-05-01.
57. Pope AT, Bogart EH. Identification of hazardous awareness states in monitoring environments. SAE 1992 Transactions. *J Aerosp* 1992;101:448–457.
58. Tvaryanas AP, Lopez N, Hickey P, et al. *Effects of shift work and sustained operations: operator performance in remotely piloted aircraft (OP-REPAIR)*. Brooks City-Base: United States Air Force, 311th Human Systems Wing, Jan 2006. Report No.: HSW-PE-BR-TR-2006-0001.
59. Barnes MJ, Matz MF. Crew simulations for unmanned aerial vehicle (UAV) applications: sustained effects, shift factors, interface issues, and crew size. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*. Santa Monica, Chicago: Human Factors and Ergonomics Society, Oct 5–9 1998.
60. Della Rocco P, Cruz C, Clemens JA. *The role of shift work and fatigue in air traffic control operational errors and incidents*. Oklahoma City: Civil Aerospace Medical Institute, Federal Aviation Administration, Jan 1999. Report No.: DOT/FAA/AM-99/2).
61. Kidd JS, Kinkade RG. *Operator change-over effects in a complex task*. Wright-Patterson AFB, Ohio: USAF Wright Air Development Center, Aug 1959. Report No.: WADC TR 59–235.
62. Wickens CD, Dixon S. *Workload demands of remotely piloted vehicle supervision and control: single vehicle performance*. Urbana-Champaign: University of Illinois, Aviation Research Lab, Sep 2002. Report No.: AHFD-02-10/MAD-02-1.
63. United States Air Force. *The U.S. Air Force remotely piloted aircraft and unmanned aerial vehicle strategic vision*. Retrieved from the World Wide Web: http://www.uavforum.com/library/usaf_uav_strategic_vision.pdf, (accessed July 17 2006).
64. Tvaryanas AP, Thompson WT. Fatigue in military aviation shift workers: survey results for selected occupational groups. *Aviat Space Environ Med* 2006;77:1166–1170.
65. Walters BA, Huber S, French J, et al. *Using simulation models to analyze the effects of crew size and crew fatigue on the control of tactical unmanned aerial vehicles (TUAVs)*. Aberdeen Proving Ground: Army Research Laboratory, Jul 2002. Report No.: ARL-CR-0483.

Summary

66. Chapanis A. *Human factors in systems engineering*. New York: John Wiley & Sons, 1996.
67. Norman DA. *The design of everyday things*. New York: Basic Books, 2002.
68. Konz S, Johnson S. *Work design: industrial ergonomics*, 5th ed. Scottsdale: Holcomb Hathaway, 2000.
69. Wickens CD. *Engineering psychology and human performance*, 2nd ed. New York: HarperCollins Publishers, 1992.

CHAPTER 24

Space Operations

Richard T. Jennings, Charles F. Sawin, and Michael R. Barratt

Somewhere, something incredible is waiting to be known.

—*Carl Sagan*

Humans have explored space for 46 years, and the effects of short- and long-term microgravity exposure on human physiology have been well documented (1,2). Humans have adapted well to spaceflight, yet physiologic decrements occur during exposure to microgravity, resulting in operational constraints for short-term space missions, and necessitate countermeasures and rehabilitation for longer missions. Many of the countermeasures have not been fully protective, yet consume valuable crew time and impact microgravity-based material science investigations. Fundamental decisions remain whether the currently envisioned countermeasures are adequate to protect and maintain crewmember productivity, safety, and return-to-Earth capability on exploration-class missions. There is an imperative that human microgravity research continue on the International Space Station (ISS), because the decision regarding a requirement for artificial gravity (AG) or short-arm centrifuge capability for long-duration exploration will ultimately drive spacecraft hardware requirements.

The increasing number of flights and crewmembers exposed to spaceflight has allowed much better characterization of relevant medical problems seen on orbit. Medical systems, flightcrew equipment, diagnostic hardware, and treatment capabilities have evolved to reflect the growing spaceflight experience base and include current terrestrial medical thinking. Although the same spaceflight environmental considerations remain, such as microgravity, acceleration, radiation, and altered atmospheric pressure, the nominal spacecraft environment is a shirtsleeve environment and the acceleration profiles are moderate. Additional information on acceleration can be found in Chapter 4. The current medical emphasis has shifted from survival issues to problems associated with extravehicular activity (EVA), radiation, episodic illnesses, isolation, physiologic deconditioning, performance optimization, and remote medical care. However, the chance for equipment failure and contingency situations outside nominal operational parameters requires adequate protective countermeasures and emergency response capabilities.

The medical operations factors for space shuttle flights, ISS crews, and exploration-class missions to the Moon or Mars are quite unique. This chapter will review the relevant human physiologic data obtained during 40 years of microgravity research plus examine the current process of astronaut selection, preventive medical care, and episodic health care delivery. Following these reviews, the medical operations programs for space shuttle, ISS, and exploration-class missions will be considered.

HUMAN PHYSIOLOGY OF SPACEFLIGHT

Cardiopulmonary Physiology

Concerns regarding possible changes in cardiopulmonary physiology have been focused on maintenance of orthostatic function and physical work capacity. Orthostatic function is of concern during entry and landing. Maintenance of adequate physical work capacity is important for on-orbit activities as well as potential emergency egress during landing. Pulmonary changes *per se* have not been very notable. Gravity affects the mechanical properties of the lung and chest wall, and changes have been reported in microgravity. Early studies in Skylab suggested that vital capacity (VC) was reduced by approximately 10% during sustained spaceflight (1). Reduced VC may have resulted from the low environmental pressure of 258 mm Hg or the slightly oxygen-enriched atmosphere (partial pressure of oxygen 170 mm Hg). A 4% reduction in forced vital capacity (FVC) was also seen in 1 G under similar environmental conditions. Pulmonary function was examined during shuttle research missions; peak expiratory flow rate, compared with preflight standing values, was reduced by 12.5% on flight day 2 (FD2) but returned to normal by FD9 (3). FVC and forced expired volume in 1 second (FEV_1) were slightly reduced on FD2 but returned to normal by FD5 and were slightly increased by FD9. Analysis of the maximum expiratory flow-volume curve showed that microgravity caused no consistent change in the curve configuration when individual in-flight days were compared with preflight standing curves. The reduction in FVC and FEV_1 during the early phase of exposure is probably due to an increase in intrathoracic blood volume caused by the cephalad shift of body fluids. In summary, no physiologically significant changes in pulmonary function have been observed during spaceflight to date.

Obtaining valid data during flight activities is more complex than in the normal research laboratory environment. Changes in diet, sleep patterns, exercise, medications, and fluid intake before and during spaceflight missions are difficult to control. Safety restrictions may make many standard research protocols inadvisable. Data collections must occur without disruption of primary mission objectives. Hardware malfunctions during in-flight data collections affect the quantity and/or quality of results. Over the last three decades, symptoms of cardiovascular changes have ranged from postflight orthostatic tachycardia and decreased exercise capacity to serious cardiac rhythm disturbances. The most documented symptom of cardiovascular dysfunction, postflight orthostatic intolerance, has affected a significant percentage of U.S. astronauts (25% for short duration missions and up to 80% for Shuttle-Mir astronauts). A basic parameter, heart rate, had previously been reported as increased, decreased, or unchanged during spaceflight. This important information deficit was corrected through systematic studies of Holter monitoring, blood pressure measurements, and related assessments of dysrhythmias, cardiac function, and orthostatic intolerance (Figure 24-1).

In a related descriptive study, 32 astronauts were evaluated with two-dimensional, directed M-mode echocardiography to determine the effects of spaceflight on cardiac volume, cardiac function, and cardiac mass. In a more operationally oriented study, 34 astronauts were instrumented with an automatic blood pressure/heart rate monitor that would permit data acquisition while the crewmembers wore their launch and entry suits (LES). The following parameters were obtained: heart rate; systolic, diastolic, and mean arterial pressure; and pulse pressure. Several important findings resulted from these descriptive studies. First, it was shown that heart rate, diastolic pressure, and their variabilities were reduced during spaceflight (4). Second, the diurnal variations of both heart rate and diastolic pressure were reduced during spaceflight. Third, monitoring records demonstrated that short-duration spaceflight did not increase dysrhythmias. Echocardiographic data showed some minor, statistically significant changes. Ejection fraction and velocity of circumferential fiber shortening did not change significantly, suggesting that spaceflight of this duration has no effect on

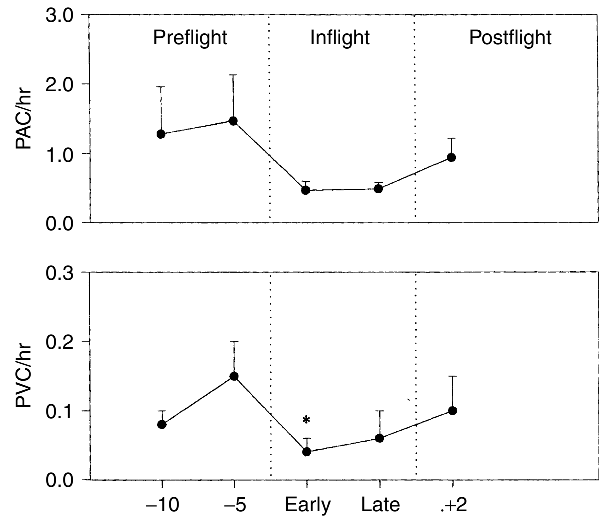


FIGURE 24-1 Premature atrial contraction (PAC) and premature ventricular contraction (PVC) occurrence. (Reprinted from Fritch-Yelle JM, Charles JB, Crockett MJ, et al. Microgravity decreases heart rate and arterial pressure in humans. *J Appl Physiol* 1996;80:910–914; with permission.)

myocardial contractility. Left ventricular wall thickness and myocardial mass index also showed no significant changes.

Standing upright for the first time after landing is associated with a significant decrease in systolic pressure. In several instances, the decrease was greater than 20 mm Hg. This occurred in 22% of the subjects on landing day, but did not occur in any subjects before flight (2). Therefore, this observed decrease in systolic pressure reflects the cardiovascular response of individuals adapted to short-duration microgravity. Many subjects used a pressurized anti-G suit during landing to support cardiovascular function. The recommended minimum inflation pressure for this protective garment was 26 mm Hg or 0.5 lb per square inch guage (psig). Most subjects inflated the suit to 52 mm Hg; this counterpressure would largely offset the hydrostatic column effect of standing in a normal gravity environment. Diastolic pressure was more adequately maintained in those who inflated their anti-G suits. There was a 70% increase in heart rate upon standing compared with the increase seen before flight. The mean standing heart rate was 120 beats/min, but a maximum of 160 beats/min was observed in one stressed crewmember.

An important cardiovascular study focused on an integrated assessment of orthostatic function (2). There were 29 participants, and 8 could not complete a 10-minute stand test on landing day because they became presyncopal (2). These subjects displayed arterial pressure and heart rate responses to standing that were similar to those seen in adrenergic failure. On landing day, their standing norepinephrine levels were significantly lower than the norepinephrine levels of the astronauts who did not become presyncopal. Plasma volumes (PVs) were not significantly different between the two groups. The group that became presyncopal on landing day had lower preflight supine and standing diastolic pressures and lower peripheral vascular resistance than the nonpresyncopal group. These data taken as a whole provide convincing evidence that the precipitating factor for orthostatic intolerance after spaceflight was a hypoadrenergic response to orthostatic stress. The parallel insufficient levels of plasma norepinephrine, diastolic pressure, and peripheral vascular resistance strongly support this. Removal of all hydrostatic gradients when entering microgravity of spaceflight produces a large headward fluid shift; this has been commonly observed and is reflected in measurements of decreased leg volume and observations of an edematous face. This fluid shift is believed to be the primary stimulus for many of the physiologic effects of spaceflight, including a reduced PV and, ultimately, orthostatic intolerance on return to Earth's gravity. It has been hypothesized that central venous pressure (CVP) would increase due to the headward fluid shift encountered upon entering microgravity. Direct measurements were made by catheter, and the results were somewhat surprising: CVP was 8.4 cm H_2O seated before flight; 15 cm H_2O in the supine legs-elevated posture before launch in the shuttle; and 2.5 cm H_2O after 10 minutes in space (5). A corollary measurement of left ventricular end-diastolic dimension measured by echocardiography showed an increase from a mean of 4.6 cm supine preflight to 5.0 cm within 48 hours in space.

Other investigators have evaluated the cardiovascular response to submaximal exercise in spaceflight (6). Cardiac output, heart rate, blood pressure, and oxygen consumption were measured repeatedly both at rest and at exercise levels approximating 30% and 60% preflight maximum. Cardiac output at rest in-flight was an average 1.5 L/min greater than erect preflight, but not different from supine preflight values. Inflight resting heart rate was an average 15 beats/min lower than the erect control value and 5 beats/min lower than the supine control value. Inflight stroke volume was elevated relative to both erect and supine control values. Inflight mean arterial blood pressure was 6 mm Hg less than erect control values, but not different from supine control values. In spaceflight, the increase in cardiac output with oxygen consumption was due entirely to an increase in heart rate. Stroke volume was not a linear function of oxygen consumption. Total peripheral resistance in-flight at rest was lower than that erect preflight but not different from that supine. One of the mechanisms responsible may have been hydrostatic unloading of dependent veins. The subjects were able to exercise in microgravity until they achieved their control maximal heart rate and maximal oxygen consumption. Mean cardiac power, expressed as the product of cardiac output and mean arterial pressure (triple product) does not appear to be a limiting factor in the increase of cardiac output with increasing levels of exercise in-flight. The maximal stroke volume seen in-flight occurred at rest; stroke volume actually declined with increasing oxygen consumption (6).

Cardiovascular countermeasure studies were conducted to determine if early inflation of the standard five-bladder anti-G suit before centrifuge simulation of shuttle landing would provide better protection against orthostasis than the standard symptomatic inflation regimen (2). Preinflation to at least 0.5 psig protected eye-level blood pressures better and resulted in lower maximum heart rates during these simulations. Although preinflation subjects exhibited a greater decrease in systolic pressure during centrifugation (–51 mm Hg vs. −36 mm Hg), they completed the runs with higher absolute systolic pressures. These findings resulted in a flight rule that now requires preinflation of anti-G suits before reentry.

The National Aeronautics and Space Administration (NASA) evaluated a liquid cooling garment (LCG) as a countermeasure to the thermal load imposed by the LES. This thermal load was believed to be largely responsible for the increased incidence of orthostatic intolerance (~25% pre-Challenger and 52% post-Challenger) noted following their introduction as standard garments following the Challenger accident in January 1986. The metabolic heat produced by an average astronaut is approximately 100 W/hr. Before use of the LCG, body heat could be dissipated only by circulating cabin air across the chest within the LES garment. This provided modest benefit in a cool cabin and no benefit after landing when cabin air temperatures often reached 27°C to 32°C. The LCG uses a thermoelectric cooler to chill water before circulating it through a full-torso, tube-filled garment. The LCG is presently worn under the new advanced crew escape suit (ACES) for launch and landing; it has proved extremely effective both for general comfort and orthostatic protection. Weight loss postflight averaged 0.7 kg less for crewmembers who wore the LCG. This difference probably represented decreased water loss due to lower sweat rates and respiratory loss during entry and landing activities. The frequency of orthostatic symptoms has decreased to pre-Challenger levels.

Alternative fluid loads were evaluated because the standard 8 g of sodium chloride diluted to be approximately isotonic in a liter of water evoked nausea and emesis in many subjects, which in turn led to decreased compliance with the flight rule requiring fluid loading before entry. Ground-based studies determined that isotonic fluids were essential. Either isotonic consommé or Astroade (potassium citrate instead of sodium chloride) was equally beneficial. Fluid loads containing natural sugars were not as effective because they induced diuresis. Hypertonic solutions often caused diarrhea. Therefore, the standard fluid load is now an isotonic fluid, 15 mL/kg preflight body weight, taken 2 hours before landing.

Experience gained during shuttle operations raised significant concerns regarding orthostatic tolerance for crewmembers returning from 4- to 6-month missions on Mir.

Soyuz vehicles return their cosmonauts in the supine position with the G-load from chest to back (positive G_x). If a normally seated astronaut or cosmonaut were to become orthostatically intolerant during entry and shuttle landing, there could be an approximate 15-minute period when no assistance would be possible. Therefore, a decision was made to use a conservative approach and return long-duration crew in the supine posture until sufficient experience had been gained to determine that this would not be necessary. NASA designed, manufactured, and provided the recumbent seating system (RSS) for use on Shuttle/Mir missions. Its use has been extended to the ISS for returning longduration crews (missions longer than 30 days). This system accommodates up to three crewmembers in the shuttle mid-deck. It was first used for the STS-71/Mir 18 mission to return one astronaut and two cosmonauts from their 115-day mission. Each subject also wore an anti-G suit that was inflated to the nominal pressure of 75 mm Hg (1.5 psi). Heart rates were approximately 25 beats/min lower than those for seated shuttle crewmembers on previous missions. Upon first standing, the crew from Mir demonstrated comparable heart rates to those from the earlier, significantly shorter shuttle missions. Systolic and diastolic blood pressures were slightly lower in the Mir crew relative to shuttle crews. These two findings indicate the protective benefit of the countermeasure. The fact that upon first standing the two groups displayed similar cardiovascular responses is encouraging; it indicates that the general cardiovascular status of the returning Mir crew was comparable with that of shuttle crewmembers.

Exercise physiology was studied because it was recognized that both physical and psychological benefits were received from in-flight exercise sessions. These investigations resulted in establishment of a flight rule requiring exercise on missions greater than 10 days in duration. A key objective was to determine the optimal combination of a crewmember's fitness before flight and in-flight countermeasures that would result in minimal performance decrements. Conducting well-controlled investigations proved extremely difficult due to multiple conflicting priorities during each mission. In general, moderate to more intense levels of cycle exercise resulted in improved submaximal exercise responses after flight. This response required exercising more than three times per week for greater than 20 minutes per session at intensities of 60% to 80% preflight maximum work loads (2) (Figure 24-2).

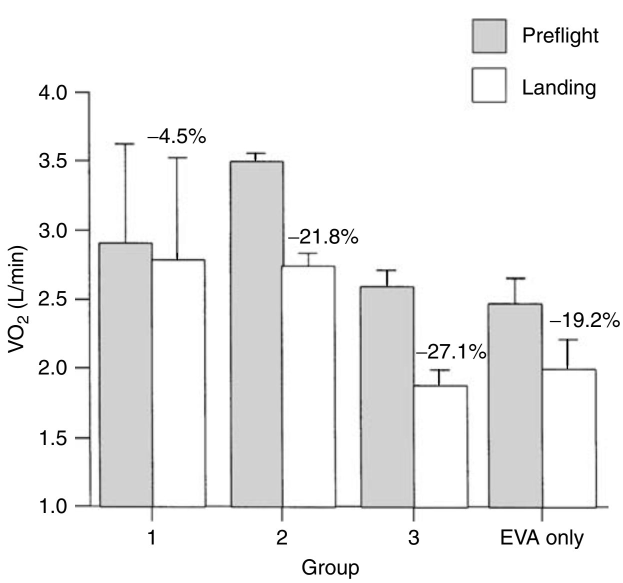


FIGURE 24-2 Aerobic capacity. EVA, extravehicular activity.

One suggested countermeasure, based on ground-based bed rest studies, required a single bout of maximal, cycle exercise 24 hours before landing. This was postulated to improve post–flight aerobic exercise response and orthostatic tolerance. Results from the initial subjects did not support the hypothesis, and further trials were canceled (2). Significant additional effort is still required to define an optimal exercise program that gives consideration to aerobic versus resistive; upper body versus lower body; eccentric (force while lengthening) versus concentric (force while shortening); high-intensity interval versus low-intensity continuous protocols; and high impact versus low impact. This information is required to determine an appropriate balance of crew risk and discomfort versus the expected physiologic benefit of the exercise.

Neurovestibular Physiology

A significant concern for operational spaceflight is the occurrence of space motion sickness (SMS). Attempts in the Russian space program to prevent SMS by selecting individuals with a high tolerance to vestibular simulation have not been successful. Applicants to the astronaut corps are not screened for motion sickness resistance. Moreover, among crewmembers who have completed preflight Coriolis testing, no correlation has been found between test tolerance and susceptibility to SMS. SMS occurs typically during the initial 3 days of spaceflight. No single drug or combination of drugs has been proved to protect all people. Promethazine, the most effective of the antihistamines, has proved very effective when taken by intramuscular injection or as a suppository. An injection of 25 to 50 mg of promethazine is now the recommended treatment for moderate to severe SMS in the U.S. space program (7,8). In summary, results obtained in both the U.S. and Russian space programs indicate that most spacecrews will experience some symptoms of SMS (>70%), and that these symptoms are brought on or made worse by head movements. These symptoms may be debilitating, and their probability of occurrence has led to operational rules that preclude EVA during the first 3 mission days. All but two cosmonauts following long flights and 27% after short flights showed symptoms on the first and second days after landing, and sometimes on the next few days as well, that could be classified as clinical vestibular dysfunctions. These symptoms consisted of illusions (e.g., dizziness, illusory movement of self or surroundings), motor reactions (e.g., pointing errors), and vestibular reactions (e.g., nystagmus of central or sometimes peripheral nature), which varied in severity. On the first day after landing, all cosmonauts complained of instability upon standing and of "swaying" from side to side while walking (9).

Flight surgeons (FSs) frequently observed disequilibrium in crewmembers during the first few hours after spaceflight. These observations were in large part attributed to functional changes in the neurovestibular system. Four primary research goals to investigate the neurovestibular system were (a) to establish a normative database of vestibular and associated sensory changes in response to spaceflight, (b) to determine the underlying etiology of neurovestibular and sensory-motor changes associated with exposure to microgravity and the subsequent return to Earth, (c) to provide immediate feedback to spaceflight crews regarding potential countermeasures that could improve performance and safety during and after fight, and (d) to design appropriate countermeasures that could be implemented for future missions. The neural processes that mediate human spatial orientation and the sensory rearrangement encountered during orbital flight are optimally studied through second- and third-order responses. The following parameters were measured during separate studies: (a) eye movements during acquisition of either static or moving visual targets; (b) postural and locomotor responses provoked by unexpected movement of the support surface, changes in the interaction of visual, proprioceptive, and vestibular information, changes in the major postural muscles through descending pathways, or changes in locomotor pathways; and (c) verbal reports of perceived self-orientation and self-motion that enhance and complement conclusions drawn from the analysis of oculomotor, postural, and locomotor responses. Spatial orientation in this context is defined as situational awareness, where a crewmember's perception of attitude, position, or motion of the spacecraft or other objects in three-dimensional space, including orientation of one's own body, is different from actual physical events. The interaction of stimuli and responses is illustrated in Figure 24-3 (2).

Perception of spatial orientation is determined by integrating information from several sensory modalities. This involves higher levels of processing within the central nervous system to control eye movements, stabilize locomotion, and maintain posture. Operational problems occur when reflex responses to perceived spatial orientation lead to inappropriate compensatory actions. Future application of effective countermeasures depends, in large part, on the interpretation of results from appropriate neuroscience investigations. A number of experimental paradigms, classified as voluntary head movements (VHMs), included the performance of (a) target acquisition, (b) gaze stabilization, (c) pursuit tracking, and (d) sinusoidal head oscillations. Target acquisition protocols used a cruciform tangent system where targets were permanently fixed at predictable angular distances in both the horizontal and vertical planes. To facilitate differentiation, each target was color coded (e.g., ±20 degrees green; ±30 degrees red, etc.) corresponding with the degree of angular offset from center. The subject was required to use a time optimal strategy for all target acquisition tasks, and to look from the central fixation point to a specified target indicated by the operator (e.g., right red, left green, up blue, etc.) as quickly and accurately as possible using both head and eye movement to acquire the target. During flight, measurements were obtained using a cruciform target display that attached to the shuttle mid-deck lockers. In all cases, surface electrodes on the face enabled quantifying eye movements that were obtained with both horizontal and vertical electrooculography. Head movements were detected with a triaxial rate sensor system mounted on goggles that

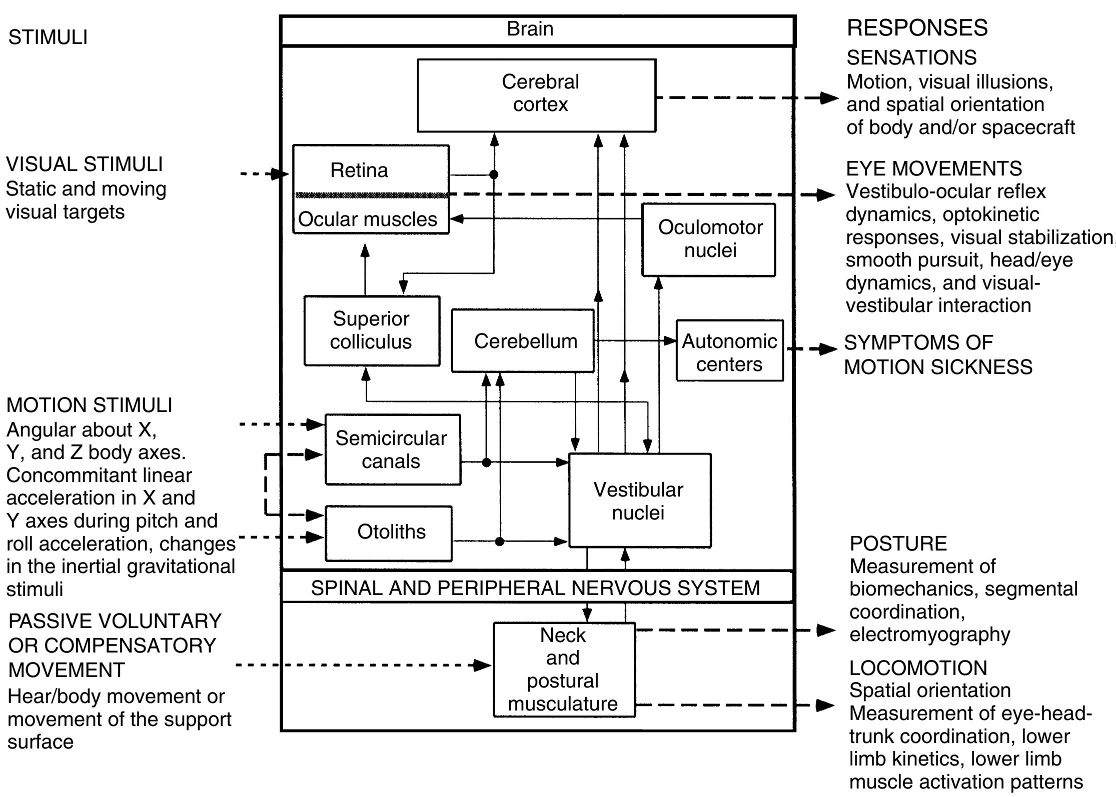


FIGURE 24-3 Central nervous system responses.

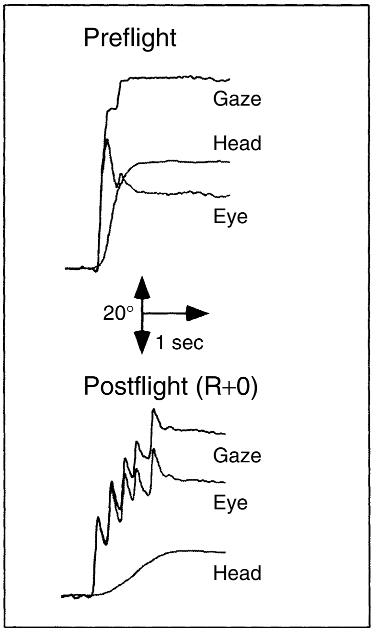


FIGURE 24-4 Saccades.

were fixed firmly to the head. Both head movements (using a head-mounted laser) and eye movements were calibrated.

Pursuit tracking, (i.e., visually moving from a central focal point to illuminated targets) was performed before flight and after flight, using two separate protocols: (a) smooth pursuit by the eyes only, and (b) pursuit tracking with the head and eyes together. In addition, a modification of these protocols used predictable, sinusoidal stimuli and unpredictable stimuli with randomly directed velocity steps. The objective was to study smooth pursuit eye movement and to evaluate its interaction with the vestibuloocular reflex. The sinusoidal pursuit tracking tasks were performed at moderate (0.33 Hz) and high (1.4 Hz) frequencies to investigate the relative contributions of eye and head movement in maintaining gaze. Significant difficulties were observed postflight, including multiple saccades (2) (Figure 24-4).

Consequently, the time required to clearly focus an image of the target on the retina increased by as much as 1 to 1.5 seconds relative to preflight times. This important finding led to discussions with shuttle commanders suggesting that they limit in particular their vertical head movements to monitor instruments during approach and landing.

Spatial orientation was tested in several ways. First, it was of interest to determine whether in space the brain is able to detect objects moving at a constant velocity as opposed to those moving at constant linear acceleration. It was found that subjects are able to successfully change their strategy catching falling objects in space. They apparently predict the velocity of the ball and also its momentum, and make an upward hand movement to catch the ball. Hand-eye coordination was tested in reaching, pointing, and grasping tasks. Amplitude, reaction time, duration, and velocity were studied while reaching for an X-Y position without seeing the hand. The amplitude of the movements was the same on earth as in-flight, but there was a slight increase in reaction time and duration, and a decrease in velocity. Two protocols investigating postural stability were performed by 40 crewmembers before, during, and after shuttle missions of varying duration. These tests used a clinical Neurocom posture platform to challenge the subject's ability to maintain balance by six different sequential tests. The first of these protocols focused primarily on reactive responses by quantifying the reflex (open-loop) response to sudden stability-threatening perturbations of base support. The second protocol focused on sensory integration by quantifying the postural sway during quiet upright stance with normal, reduced, and altered sensory feedback. After flight, tests began on landing day, as soon after the shuttle wheels stopped as possible, and were scheduled on an approximately logarithmic time scale during the subsequent 8 days (Figure 24-5).

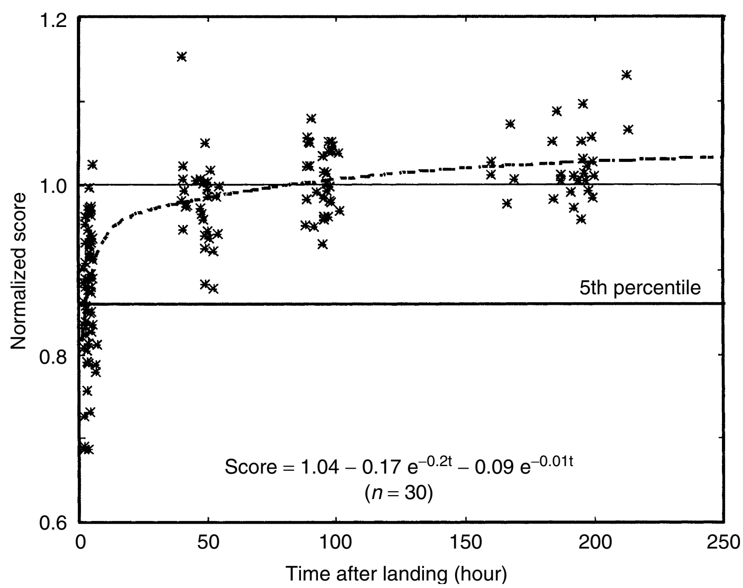


FIGURE 24-5 Balance control recovery.

The effect of spaceflight on neural control of posture was inferred from differences between preflight and postflight performance in all subjects. The effect of mission duration was inferred from statistical comparison between the performance of subjects on short-, medium-, and long-duration missions. The effect of previous spaceflight experience was inferred from statistical comparison between the performance of the rookie and veteran fliers. Astronauts with previous flight experience demonstrated better postural stability that suggested retained neurosensory learning. Centrifugation in microgravity produces linear accelerations that mimic the pull of gravity. On Earth, subjects feel tilted to the side during centrifugation that produces linear acceleration along an interaural axis, and tilted back during centrifugation when lying on their backs. This is attributable to the sum of the upward gravitational linear acceleration with the centripetal acceleration from centrifugation. On landing, there was enhanced perception of tilt. Oculomotor measures of otolith-ocular reflexes, such as ocular counterrolling, were similar before, during, and after flight. Spatial orientation to the vestibuloocular reflex in response to centripetal linear acceleration appeared to be maintained throughout the flight. These findings demonstrate that there is a strongly developed sense of orientation to gravity that persists in space (10).

Bone and Muscle Physiology

Bone and muscle respond to microgravity within the first few days of a space mission. In space, the mechanical load, or amount of weight that bones must support, is reduced almost to zero. At the same time, many bones that aid in movement are no longer used as intensely as they are on Earth. These characteristics of life in microgravity evoke two of the biggest concerns regarding the human body during spaceflight: disuse osteoporosis and muscle atrophy. Bones are relieved of mechanical loads normally experienced on Earth, and calcium normally stored in bones (which gives bones strength) is broken down and released into the bloodstream. This decrease in density, or bone mass, is called *disuse osteoporosis*. The exact mechanism by which the body divests itself of bone mass is still unknown. Current theories point to the fact that in space, old bone is absorbed much faster than new bone is laid down. The changes in bone density begin within the first few days in space. The most severe loss occurs between the second and fifth months in space, although the process appears to continue throughout the entire stay in microgravity. Bone demineralization is tracked during a mission by monitoring electrolytes; calcium in the urine serves as one marker of bone loss. Baseline bone mineral density, bone loss, and recovery are monitored pre- and postflight through imaging techniques such as dual-energy x-ray absorptiometry (DEXA). These measurements have documented losses in the lower spine and hip, posterior elements of the vertebrae, femoral neck, and tibia. Recovery of bone mass may take up to 2 years despite the fact that excess calcium no longer appears in urine soon after return to Earth. The risk of injury to long-duration flight crews is compounded by coordination and balance difficulties typically experienced upon return to Earth. The potential for falling and fracturing a bone is much higher than normal following flight, especially in those with a lower bone mass and reduced fracture threshold.

As bone mass is lost in microgravity, muscle undergoes a similar process. Numerous studies throughout the history of spaceflight have documented changes to muscle mass and architecture. In essence, the muscles used in standing, walking, and posture maintenance on Earth are relatively unused in space. These muscles begin to atrophy, becoming smaller and weaker. As a result, astronauts may lose strength and size in their muscles, ultimately extending the time for recovery of bone mass. Again, the exact mechanism behind this change remains elusive. Bone loss in spaceflight is much more accelerated than bone loss on Earth. Gender differences in spaceflight are also less pronounced than on Earth; in space, both men and women lose bone mineral at approximately the same rate. The human musculoskeletal system is a complex, multicomponent array of effector organs (including muscles), connectors (such as tendons and ligaments), and structural components (bones) responsible for the support and movement of the human body. The skeletal system provides the mechanical support to which muscles attach for movement, protects the internal organs, houses the bone marrow, and stores calcium, phosphorous, and other ions. The skeleton allows us to remain upright and move in the presence of gravity. In the presence of gravity, our bipedal stance and gait dictate that certain bone and muscle groups are essential to posture and movement. The muscles of the legs and trunk are responsible for producing the forces required for activities such as walking, running, and maintenance of an upright posture in a terrestrial setting. In contrast, arm bones and muscles are responsible for providing the forces required for activities associated with upper body balance and manual dexterity. Consequently, the functioning of bone and muscle are closely linked. It is therefore not surprising that environmental conditions affecting bone impact muscle as well. Bone is a highly vascular, constantly changing, specialized type of mineralized connective tissue consisting of two types of bone cells. Osteoblasts, cells that lay down new bone material, are responsible for bone formation, whereas the osteoclasts reabsorb old bone material. Formation and destruction of bone is an ongoing process throughout life; we typically replace approximately 20% of our bone each year. The loss of bone in space appears to be related to an adaptive process where the body senses it does not need as much bone as when it was on the ground. The hormonal regulation of calcium and bone metabolism reflects this change. At the cellular level, the decreased calcium absorption is related to decreases in circulating vitamin D. Researchers have also observed that decreases in certain hormonal levels (e.g., growth-stimulating hormone that affects the parathyroid gland) correlate with decreased bone formation. Generally accepted theory holds that our endocrine system responds to microgravity by disrupting the balance between bone resorption and bone construction, such that resorption exceeds construction. In addition, it is assumed that genetic factors also play a role in determining the extent to which bone is lost during weightlessness. Scientists have extensively evaluated the minerals that provide bones with their strength. Calcium is the primary mineral required for strong bones, so researchers have studied the amount of calcium in the body and its movement throughout the body. The excretion of calcium and phosphorous during spaceflight is increased. The rate of calcium loss from bone increases during flight. The rate of bone calcium loss is approximately 250 mg/d, which calculates to 1% to 2% mass loss per month in the lower extremities. Recovery after spaceflight is approximately 100 mg/d; therefore, the recovery of lost bone mass will take approximately 2.5 times as long as the mission duration. NASA researchers scanned the bones of 19 Russian cosmonauts who flew between 126 and 312 days on the Mir space station. Bone loss in the spine (>1% per month) exceeded that seen in bed rest subjects. Decreases in bending and torsional strength, averaging approximately 8% in the femoral neck and approximately 4.5% in the femoral shaft, also were measured. Together, these data suggest that countermeasures for maintenance of bone integrity were inadequate. Changes in bone mineral density after astronauts participated in 4- to 6-month flights on the Mir space station are shown in Figure 24-6.

Density of the skeleton was measured within the first week following flight. Mean loss was −11% in the trochanter area of the femur, −6% in the neck of the femur, −7% in the calcaneus of the heel, −7% in the pelvis, and −1% in the lumbar spine. It was documented that lumbar spine losses continued postflight for up to 6 months as other regions recovered. Final recovery to preflight density occurred for five of seven subjects. Aerobic and to some degree resistive exercises have been the primary countermeasures against bone loss throughout the history of spaceflight, but they have been only partially effective. Although the Skylab-3 and Skylab-4 crews as well as the Mir crews performed extensive aerobic exercise during flight, they showed substantial mineral losses (1). This has cast doubt on the effectiveness of the exercise program. Additional, intensive resistive exercise programs are under evaluation. New countermeasures will likely include resistive exercise directed at specific affected areas, and possibly AG. Resistive exercise is difficult to accomplish in space, and AG requires major spacecraft hardware considerations. Potential pharmacologic countermeasures are based on a class of drugs referred to as *bisphosphonates*; these drugs block the action of osteoclasts and are currently under investigation in bed rest studies (Figure 24-7).

The link between bone loss and muscle atrophy is widely accepted. The absence of mechanical strain on the lower limbs during spaceflight leads to a rapid decline in muscle mass. This decrease in muscle mass and strength appears to be a contributing factor to bone loss in space. The exact mechanism of these muscular effects on bone is unknown. There are indications of alterations in molecules used by the body to transmit information about a change in mechanical strain. For example, studies have demonstrated that levels of interleukins and insulin-like growth factor I decrease in microgravity and therefore enhance bone resorption. Microgravity also promotes enhanced absorption of calcium directly from bone, which further affects hormonal levels. It is possible that specific cells in the bone marrow may promote the formation of bone-resorbing osteoclasts. In addition, bone loss is thought to be progressive; the amount of bone loss in weight-bearing bones seems proportional to the length of flight. Unfortunately, bone loss occurs despite

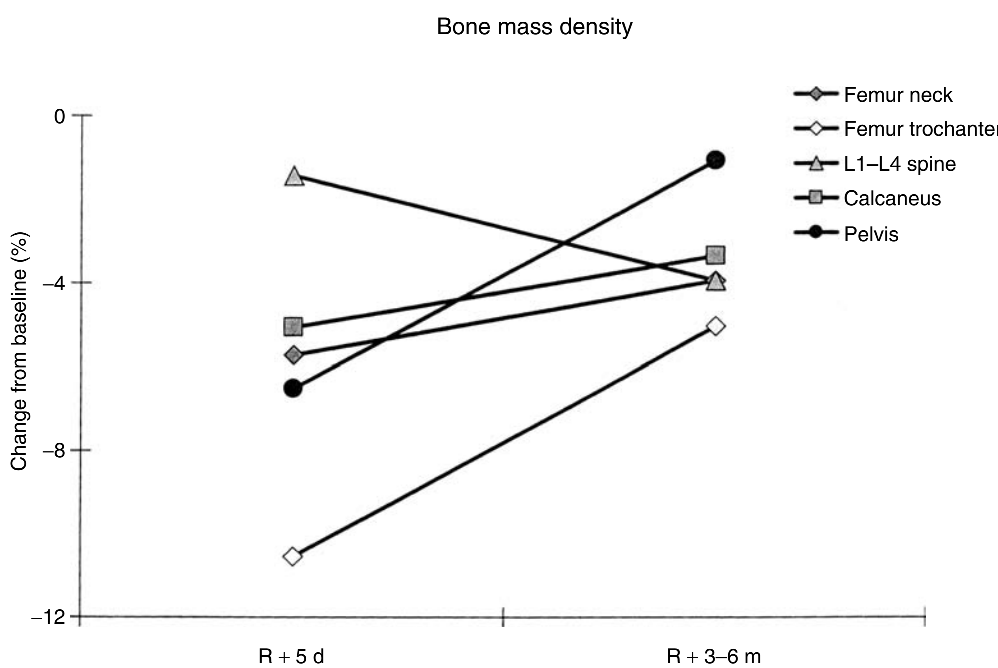


FIGURE 24-6 Bone mass density.

FIGURE 24-7 Senator John H. Glenn, Jr. pictured with the osteoporosis experiment in orbit (OSTEO) (photo courtesy National Aeronautics and Space Administration).

available countermeasures. It is projected that the loss will stop after some time, but we have yet to reach that point in the flight studies to date.

Mammalian skeletal muscle has a standard architecture developed around the contractile protein elements responsible for force production, namely *actin* and *myosin*. It is the actin-myosin ''molecular engine'' that is responsible for producing the force developed during muscle contraction. The actual process of movement is accomplished through muscle contraction. Contraction is the result of a complex chemical reaction. When movement is needed, the brain releases a neurotransmitter that communicates an electrical impulse to the muscle fiber. Thousands of fibers contract to produce movement in the muscle. This process—from the time that the signal leaves the brain to the time that the muscle contracts—takes only minutes. Movement may also be the consequence of a reflex action. In this case, the brain is not part of the signal pathway; the spinal cord is the natural connection between a reflex action and movement of the muscle. All muscles are slightly contracted during consciousness; this is referred to as *tonus*. Tonus contributes to the upright posture and keeps the muscles stimulated and healthy. Nonstimulation leads to muscle atrophy. Slow-twitch fibers are those normally associated with activities requiring endurance, such as long distance running, walking, or maintenance of posture. Fast-twitch fibers are those associated with muscle normally used for rapid movement such as sprinting or power lifting. One of the most important aspects of muscle physiology with regard to environmental challenges is the level and the type of mechanical load to which a particular muscle is exposed. Muscles adapt based on their loading histories. To better understand changes in muscle, researchers developed a breakthrough methodology to directly measure proteins involved in muscle synthesis. Direct measurement of protein synthesis rates in astronauts suggests that the normal balance maintained between protein synthesis and degradation is disturbed during spaceflight. Protein degradation rates must be significantly increased during spaceflight in order to account for the rapid loss of the muscle mass. Pre- and postflight imaging has shown dramatic reductions in skeletal muscle volume in a large number of muscle groups, including the soleus/gastrocnemius (calf muscle), hamstrings, and quadriceps (thigh) muscles after both short- (8 days) and long-duration (115 days) spaceflight. Reductions in both lean body mass and muscle volume are paralleled by a concomitant decrease in the cross-sectional area of the individual muscle fibers. Limited data, obtained from muscle biopsy from both American astronauts and Russian cosmonauts, show a reduction in muscle fiber with associated loss of contractile protein elements, actin and myosin. In addition, the loss of muscle mass is most prevalent in the antigravity muscles and is associated with a loss of muscle strength and endurance (2). There is no doubt that the removal of mechanical load from the musculoskeletal system is the most important initiating factor in skeletal muscle atrophy. Changes in muscle morphology were studied by pre- and postflight biopsy of the vastus lateralis muscle in the thigh. Significant changes were evident after 6- to 9-day shuttle missions, including a 15% reduction in the cross-sectional area of type 1 and a 22% reduction in cross-sectional area of type 2 muscle fibers. Decreased capillary density and increased ratio of glycolytic/oxidative enzymes resulted in muscle becoming relatively more anaerobic. Muscle function was measured by a Lido dynamometer. Large decrements in trunk flexor and extensor strength, both concentric and eccentric, and significant losses in concentric quadriceps extension were seen. Muscle strength typically recovered within 7 to 10 days, with the exception of concentric back extension following short-duration missions (2).

Hematology

Astronauts consistently return from space with a decreased red blood cell mass (RBCM) (11). This has been observed during Apollo missions with a 258 mm Hg (5 psia) oxygen atmospheric pressure, during Skylab with a normal sea-level oxygen partial pressure but lower total pressure environment (BP = 258 mm Hg), and finally in shuttle missions where the atmospheric composition and pressure were sea-level equivalent. During detailed studies on Spacelab missions, the observed decrease in RBCM was attributed to fewer new red blood cells (RBCs) being released from the bone marrow (11). The hematocrit, reflecting changes in the RBC count and mean corpuscular volume (MCV), did not increase significantly during flight. Six days after flight, RBC count, hemoglobin concentration, and hematocrit were all below preflight mean values. The mechanisms of action are thought to occur as follows. PV decreases, causing an increase in hemoglobin concentration that affects a decrease in erythropoietin or other growth factors or cytokines. The RBCM decreases by destruction of recently formed RBCs to a level appropriate for the microgravity environment. This represents normal adaptation to microgravity. On return to Earth, there is acute hypovolemia as vascular space dependent on gravity is refilled, an increase in PV, a decrease in hemoglobin concentration (representing "anemia"), and an increase in serum erythropoietin. Because erythropoietin is either decreased or normal in-flight, it supports the thesis that decreased RBCM is a normal adaptation to the microgravity environment. Changes after return to Earth, that is, orthostatic hypotension, rapid increase in PV, and increase in serum erythropoietin indicate that the optimal values for both plasma and RBCs are greater on Earth than in space. Normal RBC survival was documented by use of circulating chromium-tagged RBCs. Typically 1% of RBCs is replaced daily. The increase in chromium-specific activity and decrease in RBCM probably occurred as a consequence of not replacing cells that were normally destroyed.

Detailed studies of blood volume were not accomplished for the astronauts who flew 4- to 6-month missions on the Russian Mir station. However, interesting mean changes were measured pre- to postflight that were generally consistent with prior observations for other programs. Hemoglobin was decreased approximately 10% postflight. Hematocrit was decreased 4%, and the RBC count was down approximately 6%. There was no apparent change in MCV.

Fluid and Electrolyte Balance

Water diuresis was expected to occur early in-flight but was not observed in Skylab crews. Osmolality of the urine formed was higher than that of plasma, averaging 300 mOsm higher than preflight. Generally, 24-hour urine volumes indicated that crewmembers excreted volumes similar to their preflight control values. Plasma sodium was generally decreased throughout the flight, and potassium demonstrated a trend toward becoming slightly though not statistically significantly elevated. The loss in potassium was also demonstrated by decreased total body exchangeable potassium. There was an increased aldosterone secretion that probably caused the potassium loss. Slight increases were observed in plasma creatinine, indicative of slight decreases in creatinine clearance. In turn, this may reflect minor alterations in renal function in-flight.

Calcium and phosphorous levels were significantly elevated in the plasma as in the urine throughout the in-flight and early postflight phase. Urinary epinephrine level was generally normal or decreased in-flight and elevated postflight. Norepinephrine was more variable but did show periods of increase during the flight and significant increases post flight. It is well established that epinephrine is most often associated with anxiety responses whereas norepinephrine is more closely related to physical stress. The in-flight norepinephrine levels are probably the reflection of the high levels of physical exercise undertaken by the crewmembers. In summary, although significant biochemical changes were observed, they varied in magnitude and direction, and all disappeared shortly after return to Earth. Fluid and electrolyte balance, renal function, calcium balance, and energy utilization are all affected by spaceflight, although clinically important alterations are rarely observed. For the most part, these changes are thought to be indicative of successful adaptation of the body to the combined stresses of weightlessness; the human body seems to adapt so successfully to the weightless environment that return to gravity on Earth causes more concern than living in space (1).

Nutrition

Skylab was a prototype space station flown in the early 1970s. There were three missions, Skylab-2, -3, and -4, with three astronauts each and lasting 28, 59, and 84 days, respectively. For each of the three Skylab missions, a metabolic balance study was performed beginning at least 21 days preflight and continuing until 17 days after return for the nine astronauts. Variables monitored included diet, fluid, and electrolyte balance, various hormones, and nitrogen balance. The Skylab investigators found that the protein loss was greatest during the first month, but continued for the duration of the mission (1).

These Skylab data for the first 12 days were compared with studies conducted on 1- to 2-week Shuttle missions (12). There was no statistically significant difference in the preflight dietary intake or estimated nitrogen balance between the two groups, although there may have been a trend for nitrogen balance to be less for the shuttle astronauts. Although energy intake was higher on Skylab, the nitrogen loss was greater. Over the entire duration of the Skylab missions, urinary nitrogen excretion was increased by 3.1 g/d above the preflight control period. With the shuttle, the decreased nitrogen balance paralleled the decreased protein intake (12). Therefore, it is clear that energy intake and nitrogen balance were different between shuttle and Skylab, and when the estimated nitrogen balance is used as the criterion for comparison, shuttle crews fared better. Skylab astronauts individually developed a prescribed daily exercise regimen, which increased in intensity from Skylab-2 through Skylab-4. This daily exercise regimen was not required or prescribed. Each crewmember selected his own mix of equipment utilization and specific protocols with advice from ground monitors. For Skylab-2, only a cycle ergometer was available; for Skylab-3, an apparatus referred to as a *mini-gym* that provided some resistive exercise was added. A simulated treadmill was added for Skylab-4. This device was a Teflon-coated metal plate that the subject slid his stocking-covered feet across while maintaining position with a bungee cord restraint harness designed for the ergometer.

It was uncertain how the combined effects of limited physical activity and perhaps increased stress would affect nutritional requirements. Earlier spaceflight studies indicated changes in protein turnover that were consistent with a stress reaction during shuttle flights. Estimated water turnover (important inflight due to concerns about the potential for renal stone formation) was a by-product of the nutritional studies. Various experts have recommended inflight water intake of at least 2,500 mL/d. Rehydrated food and fruit drinks provide approximately 80% of this fluid intake.

Energy expenditure requirements were determined for 13 male astronauts 36 to 51 years of age during spaceflights 8 to 14 days in duration (2). Methods used were developed from the doubly labeled water (DLW) technique modified to account for baseline isotopic differences associated with the shuttle potable water system. The analytic uncertainty of the DLW method performed in ground-based laboratories is $\pm$4.5% actual average metabolic rate. The slightly higher isotopic doses used for these studies reduced the uncertainty to approximately $\pm$3.5%. Baseline metabolic studies were accomplished approximately 2 months before flight, whereas flight studies typically began on the third flight day to avoid confounding effects associated with SMS. The energy requirements associated with physical activity in microgravity were largely unknown, and the relatively close confines of the spacecraft tend to limit the extent of physical activity. Ambient temperature and relative humidity are held relatively constant within the shuttle at 21°C to 24°C and 20% to 30%, respectively. During flight, energy intake (8.8 $\pm$ 2.3 MJ/day) was less than flight total energy expenditure (11.7 $\pm$ 1.9 MJ/day; $p < 0.005$). Body weight was less at landing than at 2 days before launch (76.5 $\pm$ 6 kg compared with 78 $\pm$ 6 kg, respectively; $p < 0.05$). No statistically significant differences were found between ground-based and inflight energy expenditures.

The loss of body weight has been a consistent finding with spaceflight. Some of the weight loss is due to the loss of fluid, but there is also the loss of lean body mass and some loss of strength, particularly in the postural muscles. Astronauts are in negative nitrogen balance during spaceflight. The protein loss is of concern because it could limit the duration of human spaceflight. The principal approach to reducing the inflight muscle loss is to follow an aggressive, time-consuming exercise program inflight. Russian crews typically exercise for at least 2 hr/d. The costs of such a program are considerable in terms of the extra food, the capability for disposal of the metabolic waste products, and the time spent exercising. Although it is generally believed that exercise can attenuate the protein loss, there have been no specific inflight tests with appropriate controls to determine efficacy of current exercise regimens.

Any crewmember who is in negative energy balance (i.e., whose energy expenditure exceeds energy intake) will lose lean body mass regardless of the type, frequency, or intensity of exercise regimens or protein consumption. Results from Skylab suggest that crewmembers can and do lose weight during flight despite the consumption of adequate calories (energy) and protein. The weight lost as a result of microgravity exposure generally consists of body fluids and electrolytes, RBCs, and muscle or lean tissue. A significant portion of in-flight weight loss, even during relatively brief missions (up to 10 days) is thought to be due to loss of lean body mass. One important cause of loss of lean body mass is being in negative energy balance. Loss of lean body mass reduces muscle work capacity and promotes loss of electrolytes, especially potassium, which affects muscle and cardiovascular function (12).

Interpretation of body weight changes during spaceflight was confounded by the fluid-loading countermeasure, although typically most fluid load was lost through a combination of diuresis and perspiration. Total weight loss, recorded at landing, reflects a combination of tissue and water loss. Furthermore, it has previously been shown that relative proportions of energy sources shifted during flight, with the carbohydrate component increasing, protein remaining stable, and fat declining. The poorer nitrogen retention for Skylab crews, despite greater food intake relative to the shuttle crews, suggests inadequate intake relative to added energy costs of the overall exercise. During spaceflight, as on the ground, inadequate energy intake coupled with exercise will exacerbate the loss of body protein. Energy costs of normal living in space are probably lower than on the ground for comparable activity. The difference between exercising and "normal living" in space is that the exercise has to be done in a prescribed way, whereas with normal living the subject is free to use multiple modes. An inflight exercise program may be counterproductive for attenuating the spaceflight-induced

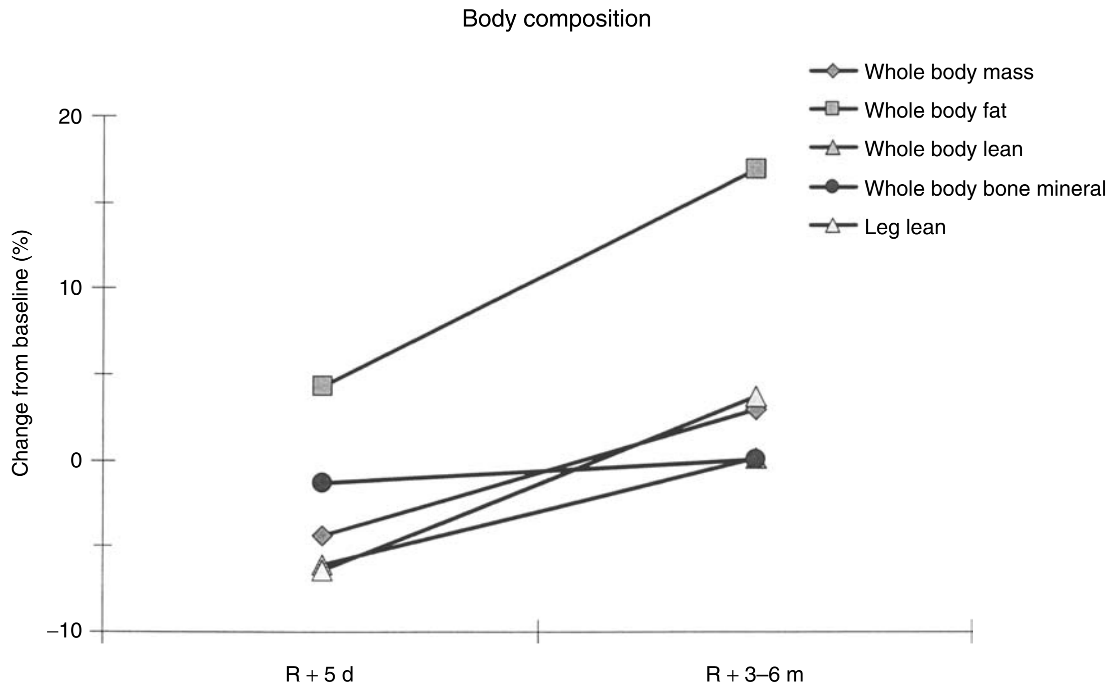


FIGURE 24-8 Body composition.

protein loss unless the associated increased energy needs can be met. Figure 24-8 summarizes mean changes in body composition as measured postflight in seven Shuttle-Mir astronauts.

Renal and Gastrointestinal Physiology

Exposure to the microgravity environment of space produces a number of physiologic changes of both metabolic and environmental origin that increase the potential for renal stone formation. Metabolic, environmental, and physicochemical factors that influence the risk for developing renal stones were examined in 24-hour urine samples from astronauts 10 days before launch and on landing day, to provide immediate assessment of these factors (2). Decreased fluid intake and vomiting associated with SMS in some people during early phases of spaceflight probably contribute to decreases in urine volume, thereby increasing the risk of stone formation. Urinary calcium levels increase during flight, reflecting the overall negative calcium balance. Several of the physiologic changes that take place during human exposure to microgravity are thought to affect the factors that contribute to the risk of renal stone formation, especially changes in urine volume or urinary calcium, phosphate, potassium, and sodium excretion. For example, urinary calcium concentrations begin to increase within 24 hours of exposure to microgravity; urinary phosphate levels also tend to be higher during flight than before. Both of these imbalances probably reflect the bone demineralization process, and both increase the potential for urinary saturation of calcium oxalate and calcium phosphate. Additional factors that could aggravate stone formation potential in astronauts include diets high in animal protein, frequent exercise, loss of lean body mass, and varying degrees of dehydration. Metabolic factors, so named because a change in their excretion is usually of metabolic origin, include urinary calcium, oxalate, uric acid, citrate, and pH. Risk factors that can be influenced by environmental factors include total urine volume and urinary sodium, sulfate, phosphorus, and magnesium. These metabolic and environmental factors are used to calculate physicochemical risk factors, for example, the super saturation of calcium oxalate, brushite (calcium phosphate), monosodium urate, undissociated uric acid, and struvite. A group of astronauts participated in pre- and postflight urine collections to assess renal stone risk. Average age of the 76 male and 10 female astronauts was 42.2 years. All crewmembers consumed a high-protein (>100 g/d) and high-sodium (>10 g/d) diet during their missions. Total fluid intake from foods and liquids was approximately 2 L/d or less. Crewmembers "fluid loaded" approximately 90 minutes before landing by ingesting a liter of physiologic saline. Statistically significant changes were shown for pH, calcium, and citrate in the direction of increased stone-forming risk (2) (Table 24-1).

Urinary citrate, a known inhibitor of renal stone formation, was lower after spaceflight (575 ± 31 mg/d) relative to before flight (707 ± 33 mg/d, $p < 0.0005$); this compounded the effects of increased calcium secretion. The observed decrease in mean urine volume from 1.94 ± 0.13 L before flight to 1.63 ± 0.09 L at landing ($p < 0.0018$) suggests that renal stone risk increased, due to concentrating urinary salts. There were some indications that length of flight increased risk also, particularly in the case of increased urinary saturation of calcium oxalate. At landing, crewmembers exhibited hypercalciuria, hypocitraturia, decreased

TABLE 24-1

Pre- to Postflight Changes in Renal Stone Risk Factors

Variable	Launch–10 Days	SEM	Day of Landing	SEM	n	p Value
Calcium (mg/d)	190	9.50	213	11.8	86	0.0159
Oxalate (mg/d)	33.7	1.87	34.6	2.30	85	0.6092
Uric acid (mg/d)	630	22.0	558	24.7	86	0.0047
Citrate (mg/d)	707	32.6	575	30.9	86	0.0002
Ph	5.98	0.04	5.58	0.04	86	<0.0001
Total volume (1/d)	1.94	0.13	1.63	0.09	86	0.0018
Sodium (mEq/d)	148	6.3	103	5.7	86	<0.0001
ulfate (mmol/d)	21.3	0.73	26.1	1.05	86	<0.0001
Phosphorous (mg/d)	1.016	66.9	953	37.1	86	0.4084
Magnesium (mg/d)	112	4.0	92	4.1	86	<0.0001
Creatinine (mg/d)	1,667	39.7	1,791	60.0	86	0.0271
Potassium (mEq/d)	65	2.34	52.6	2.39	86	<0.0001
Relative supersaturation						
Calcium oxalate	1.68	0.13	2.51	0.18	85	<0.0001
Brushite	1.43	0.15	1.00	0.11	86	0.0029
Sodium urate	2.98	0.31	1.61	0.14	86	<0.0001
Struvite	1.93	0.56	0.36	0.07	86	0.0061
Uric acid	2.09	0.20	3.35	0.20	86	<0.0001

SEM, standard error of the mean.

magnesium excretion, and decreased urinary pH and volume. A decrease in pH typically increases stone-forming potential by decreasing the solubility of uric acid and increasing the availability of uric acid crystals, which in turn can act as a nidus for calcium oxalate stones.

Another issue in regulatory physiology is associated with gastrointestinal (GI) function. The GI tract has a central role for maintaining energy balance by absorbing nutrients from food and other consumed substances in forms that the body can use. Changes in GI mobility and gastric secretion can result in decreased appetite, as well as malabsorption of amino acids, fats, vitamins, fluids, electrolytes, and many medications, which in turn affects the bioavailability of these substances. The absence of a gravity vector in spaceflight, coupled with the corresponding changes in body posture and fluid distribution, may reduce GI mobility. GI mobility has two distinct components: (a) gastric emptying (GE) rate, which is the rate at which the stomach contents empty into the small intestine, and (b) intestinal transit time, which is the rate intestinal contents move from the small bowel to the cecum. GE rate is known to be slower in supine subjects. GE rate was determined in limited subjects by administering an oral dose of acetaminophen and following salivary concentrations as it is absorbed through the intestinal wall (2); the absorption rate of acetaminophen after oral administration has been shown to be directly proportional to GE rate. Intestinal transport time was measured using lactulose, a nondigestible sugar (one that passes undigested through the small intestine). Bacteria in the colon ferment the lactulose, producing hydrogen that is exhaled by the subject. The period between the ingestion of lactulose and peak rise in breath hydrogen represents mouth-to-cecum transit time. Both tests together permitted assessment of GI function. Preliminary conclusions from a few subjects indicated that GI function was slightly depressed in microgravity.

Circadian Rhythm Alterations

Circadian rhythms are another component of regulatory physiology that may impact human performance. Efforts to maximize crew time during flight have included shifting work–rest schedules before flight to allow round-the-clock operations. People who work in 24-hour operations consistently demonstrate drowsiness, fatigue, sleep disturbances, and impaired performance and mood. Human circadian patterns can be altered by different methods: modifying the sleep period gradually over time with corresponding shifts in the work schedule or shifting by periodic timed exposures to bright light (7,000–12,000 lux). Bright light can shift cycles of body temperature, cortisol, and melatonin release, markers of circadian patterns. Plasma melatonin is a good indicator of shifts in human circadian rhythms. The endogenous melatonin cycle is known to be sensitive to light and darkness, and seems to cycle in synchrony with core body temperature. Measurements of melatonin peaks (acrophases) and cortisol demonstrated that use of bright lights could effectively shift circadian rhythms over an approximate 7-day period. Phase delays of 11 to 15 hours have been achieved. Astronauts sleep less in space, typically 6 to 7 hr/d versus 8 hr/d on Earth. Sleeping habits of astronauts have been monitored, and a double-blind study was conducted to evaluate whether sleep loss could be treated with melatonin. It was found that melatonin has no effect on the quality or duration of sleep in space. Decreased sleep could contribute to performance errors. The quality of sleep was normal, and there was adequate rapid eye movement (REM) time during sleep. All other measures of sleep topography were also normal. There is likely no inherent difficulty in sleeping in space, but there are high workloads and interesting tasks that inhibit going to bed early. Eventually, overscheduling will degrade performance. Respiratory studies conducted during sleep and awake states indicated a strong coupling between the control of ventilation and the quality of sleep. The amount of sleep-disordered breathing was also reduced in space compared with normal gravity, perhaps because removal of the weight of the structures around the upper airways resulted in less airway obstruction (2).

Russian System of Countermeasures Approach

The Russian System of Countermeasures (RSC) approach is designed to preserve the health and efficiency of the cosmonauts. They are currently evaluating the relative efficiency for each component of their program (e.g., running on a treadmill, cycle ergometry, and resistive exercises). A key facet of their program is that gravitational unloading induces an acute decrease in afferentation, including proprioceptive afferentation. The RSC presently embodies 4-day training microcycles (alternating treadmill, cycle, and resistive exercises) as well as application of the Penguin loading suit. The Penguin suit is a full body garment that incorporates rubber bungee cords that can be adjusted to provide loading across various muscle groups. The RSC approach also includes application of measures to redistribute body fluids and correct water and salt metabolism through sessions using lower body negative pressure (LBNP) (Chibis garment) in combination with water and salt additives. The RSC has evolved during more than 65 missions to Salyut and Mir orbital stations for durations of 60 to 438 days. The Russian scientists found inconsistent correlation between flight duration and persistence or magnitude of bodily changes. However, physiologic changes correlated well with volume and intensity of inflight physical exercise, especially during the final stage of flight. In fact, Russian scientists largely ignore the initial 3 to 4 weeks inflight and prefer to allow normal adaptation to the microgravity environment without interceding. They have noted that weightlessness conditions lead to modification of the activation patterns of various muscles, and energy requirements may be greatly altered. These scientists believe that locomotor patterning exercises are of greatest importance, followed by resistive training with relatively less emphasis on aerobic training on the bicycle or treadmill. System optimization requires striking an appropriate balance between these exercise modes. These emphasis become apparent when one examines the timelines associated with each mode of training. It can be readily determined that the duration and intensity of most sessions would not support significant aerobic training.

Artificial Gravity

Application of AG during spaceflight has long been considered the potential "silver bullet" countermeasure. Philosophically, one could assume that removing the primary difference between spaceflight and Earth by adding appropriate levels of AG would obviate the need for other countermeasures, with the possible exception of radiation shielding. Appropriate levels of AG should maintain optimal physiologic function. However, several uncertainties remain as follows:

- What are the physiologic thresholds for effective gravitoinertial force?
- What minimum or optimum gravitoinertial force should be used during transit phases of missions?
- Would AG be required on the lunar or Martian surface?
- What are the untoward physiologic consequences of rotational AG?
- What additional countermeasures, if any, would be required to supplement AG?

Requirements for long-arm, continuous AG may be different from those for short-arm, intermittent AG. Feasibility assessments have been proposed to use intermittent centripetal acceleration as AG during spaceflight. Current proposals plan to evaluate a combination of moderate aerobic exercise with centripetal acceleration as AG for a combined countermeasure and an initial study using AG as a countermeasure in bed rested individuals showed promising results. There may be tradeoffs between neurovestibular risks (motion sickness, disorientation) versus the reduction in postflight deficits. Eventually, studies that examine the tradeoffs between risks and benefits of AG must be explored with respect to bone, muscle, neurovestibular, and cardiovascular functions. These are complex investigations, and correctly meeting their inflight requirements will severely limit other biomedical activities on those missions. Nevertheless, a group of preeminent scientists recently concluded that NASA should sponsor a rigorous, peer-reviewed research program to systematically investigate rotational AG as a multidisciplinary countermeasure during long-duration space missions.

ASTRONAUT SELECTION AND HEALTH MAINTENANCE

The medical selection of astronauts and spaceflight participants has become much more complex in recent years due to the wide variety of mission durations, variation in on-orbit duties, operational anthropomorphic constraints of the Soyuz vehicle, EVA suits, and pressure suits, as well as the wide range of career length expectations. The emerging possibility of commercial spaceflight and spaceflight tourism has widened the need for realistic medical standards beyond those provided for career astronauts by agencies such as NASA, the ISS partners (IPs), Russian space program, and the military. In addition, the trend toward international crews and long-duration missions to the Mir spacecraft and the ISS have required the development of common standards and cooperative certification efforts by the FSs from the participating countries.

Medical standards for spaceflight are dynamic and are changed as the space program's mission evolves, as more medical information is obtained about the effect of microgravity on humans, and as new medical diagnostic and therapeutic modalities emerge. One of the more difficult decisions to be made in the next several years will be how to optimize the integration of family history, physical and laboratory findings, and current genetic data to help predict future disease or disability in astronauts being considered for initial selection or assignment on long-duration space missions.

The U.S. medical standards for spaceflight usually undergo major revision every 5 years with minor changes made as needed every 2 to 3 years (13). Selection standards were initially used for the selection class examined in 1977 and have generally been relaxed over time, particularly the vision constraints. The extensive medical testing that was required during Mercury, Gemini, and Apollo has become more focused and includes recent technology such as ultrasonography, with less dependence on radiographic studies. The standards are more stringent for career astronauts than those who would fly for a single flight such as payload specialists or spaceflight participants. Pilot astronaut candidate and mission specialist candidate standards differ only for visual acuity and height parameters. In addition, the astronaut medical selection standards are more restrictive than retention standards and reflect the desire that crewmembers' careers not be adversely affected unless the medical problem precludes safe operations. Individuals who are outside the medical standards may obtain a waiver for that condition if a thorough assessment of the problem reveals that it can be treated, mitigated, or does not interfere with duties. A waiver may require limitation to duties and additional medical surveillance than the usual annual examination. Specific additional standards are now being applied to career astronauts who plan long-duration missions, and it is likely that many astronauts who are medically cleared for short-duration missions will not be approved for long-duration missions (30 days to 6 months) where there is limited return-to-Earth capability and the mission impact of an emergency return would be dramatic. NASA and the ISS International Partners have recently developed and published new medical standards for commercial passengers traveling to the ISS. The FAA and other organizations have developed guidance for commercial spaceflight operators. Most of these operations for the near future will be suborbital flights. Commercial spaceflight participants are much more diverse by age and medical history than career astronauts, and the guidance more general in nature. The goal is to assure safe contingency egress, appropriate intergration with the vehicle and flight hardware, appropriate health and fitness to perform well during launch, entry, and landing, with a low chance to impair the mission.

Medical Standards

Space Shuttle

Space shuttle standards were developed for astronauts who fly on the shuttle. The purpose of shuttle selection and retention standards is to address two specific questions: Is the individual currently fit to fly, and will he or she be likely to complete a 10- to 15-year career without developing disqualifying medical conditions? These were the first U.S. spaceflight medical standards and are generally considered "minimum standards." While the earlier programs did not have written standards, the evaluations for Mercury, Gemini, and Apollo astronauts were designed to find those best qualified. The shuttle-era standards were designed to widen human access to space and eliminate individuals only if they did not meet the minimum. These standards also reflect the shuttle's shirtsleeve cabin environment, modest G profiles for launch and entry, and its ready return capability. Pilot standards are designated class I, mission specialists class II, payload specialists class III, and spaceflight participants class IV.

International Space Station/Expeditionary (More than 30 days)

Standards for the ISS have additional constraints, particularly for anthropometry. The maximum permissible standing height is 164.0 to 182.0 cm (64.6–71.7 in.), and the maximum seated height is 94.0 cm (37.0 in.).

For expeditionary missions, the additional constraint of long-duration microgravity exposure and limited medical diagnostic and treatment capabilities becomes important. In addition, the Soyuz vehicle and Orlan space suit have led to anthropometric constraints on crew selection. Because the Soyuz capsule will be the rescue vehicle for ISS in the foreseeable future, certain crewmembers will not be available for assignments to ISS, and constraints based on total height and seated height will probably be required for upcoming selection classes. Additional information regarding ISS and international crewmember medical certification is provided later in this chapter.

Astronaut Selection

The selection medical evaluation begins with a health-screening questionnaire submitted as part of the application process (14). Military candidates, through their nominating service branches, submit a more complete medical evaluation, including longitudinal medical data. These data are prescreened by a NASA FS. Civilians who do not have disqualifying medical conditions and who are deemed "highly qualified" by the astronaut selection board are asked to complete a physical examination similar to an FAA third class examination. Following review of this examination by an FS, those remaining qualified individuals form the pool from which the selection board selects astronaut candidate finalists. Individuals selected as finalists undergo a medical examination, interview, and familiarization tour at the Johnson Space Center (JSC) in Houston. Beginning with the ISS class selection cycle in 2008, a second more focused series of medical testing will be accomplished that includes specific tests needed for medical certification of extended duration crews. Although some research has been conducted regarding "select-in" considerations for predicting successful performance during psychological screening, the current evaluations are conducted to rule out disqualifying medical defects. Waivers to individuals outside the medical standards are not usually offered during selection. The medical examination of each finalist is presented to the JSC Aerospace Medicine Board for final determination of qualified or disqualified status. The board's decision is communicated to the astronaut selection board, and the astronaut class is selected from the pool of those found medically qualified. Approximately 75% of astronaut finalists are deemed medically qualified. The leading cause of medical disqualification during selection has been due to vision problems, and distant visual acuity limitations are the most prevalent. The initial selection physical examination serves as a baseline for following the crewmembers throughout their careers and for comparison in the Longitudinal Study of Astronaut Health (LSAH).

Preventive Medicine Programs

Annual Certification

Following selection, each astronaut is required to complete an annual medical examination by an FS during his or her birth month. The annual examination includes a history and physical examination, laboratory evaluation of urine and hematologic parameters, audiogram, ophthalmologic and dental evaluations, resting electrocardiogram (ECG), and pulmonary functions. Certain tests are performed on an intermittent basis based on the crewmember's age or risk factors. These include maximal exercise stress testing, proctosigmoidoscopy, bone densitometry, and mammography. An effort is made to perform radiography only when clearly medically indicated because the crewmembers are exposed to radiation inflight, and there are career limits to total radiation exposure.

Each year, a brief physical fitness assessment is included in the examination. This assessment includes studies for muscle endurance, flexibility, and aerobic fitness. In addition, at specified intervals preflight, inflight, and postflight, more extensive physical fitness testing—including agility tests, functional fitness tests, isokinetic strength tests, and examinations of aerobic capacity—is performed. The results of these studies are used to tailor training, determine individual responses to training, define on-orbit countermeasures, and plan rehabilitation postflight.

Wellness Program

Although the number of astronauts with serious medical problems is small, there is an increasing trend to providing wellness programs and performing health risk appraisal and aggressive intervention in crewmembers with risk factors such as hypercholesterolemia or hypertension. As in any practice, the first consideration is given to optimizing diet and activity, but most of the current medications for hypertension and elevated lipids are generally acceptable for flight, and the FSs are not precluded from their use. One of the first programs singled out for the wellness program has been hearing conservation. Crewmembers' audiograms are tracked annually, and action is taken for specialty consultation, intervention, and follow-up. On the basis of the relatively young age of the astronauts, the results of these prevention programs may not be dramatic during the crewmember's active assignment in the space program, but should have an impact on his or her long-term health and productivity. All astronaut physical examination results are periodically reviewed by the Aerospace Medicine Board, and any finding outside the NASA medical standards for retention are considered for waivers or appropriate intervention.

There are also specific preflight examinations before shuttle flights on launch minus 10 days and launch minus 2 days and after flights on the landing day and landing plus 3 days. The preflight studies for ISS are much more extensive and begin early in the mission flow.

Longitudinal Study

As Earth-bound humans ventured into space, exposure to new and novel environments in the training and flight phases of missions occurred. Some of these factors included microgravity, high-energy particle radiation, acceleration, altered atmospheric pressure and breathing gas mixtures, moon dust, iodinated water supplies, and occasionally hypergolic fuel exposure. It has been prudent to track the health of individuals exposed to space travel, and the LSAH has been ongoing to accomplish this task (15).

In order to form a comparison group for the astronauts, a group of civil servants at the JSC were selected. Three individuals from JSC matched for age, body size, gender, habits, physical activity, and length of NASA service were selected as controls for each astronaut. Because these individuals undergo annual evaluations that are similar to those for the astronauts, they constituted an adequate control group. Unfortunately, this group does not receive the same health care as the astronauts and have not gone through the rigorous selection examination, so the pools are not completely comparable.

It is hoped that tracking morbidity and mortality data from this study can help define any long-term risks related to space-flight or spaceflight training. In addition, the data may be helpful in planning for health care systems and emergency return capabilities for long-duration missions or exploration-class missions. Both the astronaut and control group data have been useful for defining preventive and interventional health programs at JSC. To date, the major difference between the groups have been the number of deaths due to trauma-related accidents. Ten active or retired crewmembers have died as a direct result of spaceflight-related activities, whereas nine deaths have occurred in aircraft accidents. Two others died in motor vehicle accidents, and another died of altitude-related complications while climbing Mount Everest.

SPACE SHUTTLE MEDICAL CARE

Biomedical Parameters of the Space Shuttle

The space shuttle design allows for a shirtsleeve environment, but egress considerations require the use of either an LES or ACES during launch, entry, and landing. On orbit, the cabin atmosphere is nominally 760 mm Hg (14.7 psig) with 21% oxygen and 79% nitrogen. Gases are produced from cryogenic supplies onboard. Carbon dioxide is usually controlled below 7.5 mm Hg. Carbon dioxide may be removed by lithium hydroxide canisters or by regenerative carbon dioxide removal beds. EVAs from the shuttle have usually been conducted at a reduced cabin atmospheric pressure of 10.2 psig, but EVAs for construction of the ISS will more often be performed from 14.7 psig. Unless there are multiple failures, the temperature and humidity of the shuttle are easily controlled to crew comfort. Multiple contingencies can occur in the shuttle that could lead to environmental extremes. These include loss of cabin pressure, altered oxygen concentration, inability to remove carbon dioxide effectively, or loss of thermal and humidity control. Flight rules and contingency plans are constructed to best protect the crew's health and safety while assuring the optimum possibility of mission success. Further information on the spaceflight environment and spacecraft environmental systems can be found in Chapter 9.

Acceleration forces during launch and landing are minimal when compared with the launch or entry forces in the early space program. Shuttle main engines throttle at +3 G_x during launch, and the G forces are most often between +1.4 and +1.6 G_z during entry. The unique aspect of shuttle entry is the prolonged acceleration due to the time required for aerobraking versus the shorter more ballistic high-G_x entry experienced during the Mercury, Gemini, and Apollo programs.

Crew Medical Training

Shuttle crew medical training is divided between training for all crewmembers and specific hands-on training given to two crewmembers who are designated crew medical officers (CMOs). The extent of training required is determined by the relatively short duration of the missions, limitations of the onboard shuttle orbiter medical systems (SOMS) kits, continuous communication capability, and ready return-to-Earth potential.

Throughout the career of an astronaut, there is an attempt to develop his or her overall aeromedical expertise. New astronaut classes include lectures on the physiologic and medical factors associated with spaceflight, including neurovestibular changes, cardiovascular deconditioning, orthostatic intolerance, fluid shifts, SMS, bone demineralization, and musculoskeletal atrophy. Each astronaut is also provided physiologic training that involves briefings on barometric pressure changes, hypoxia, hypercapnia, barotrauma, and evolved-gas disorders. In addition, they are trained to recognize their individual symptoms related to both hypoxia and hypercapnia with monitored altitude chamber exposure and exposure to hypercarbia. Each astronaut completes land and water survival training and gets several zero-G familiarization flights in the KC-135 aircraft.

At the time a crewmember is assigned to a flight, there are several general sessions that are arranged for the entire crew. The crew is provided training in cardiopulmonary resuscitation and first aid. Approximately 6 months before launch, the lead FS assigned to the mission (crew surgeon) provides a general briefing to the crew to give them an overview of the current thinking regarding biomedical concerns of spaceflight. Some of these issues include SMS, on-orbit treatment capabilities, back pain, radiation, fluid shift, EVA operations and decompression sickness (DCS), orthostatic intolerance and available countermeasures, toxicologic risks, and information regarding launch and landing emergency medical support. This session is repeated 10 days before flight with a brief review. At this time, issues such as G-suit operations, fluid and salt loading protocols, LCGs, radiation dosimeters, private medical conferences (PMCs), crew carry-on medications, the circadian shifting program, and health stabilization program (HSP) are emphasized.

Two crewmembers are designated as CMOs for each shuttle crew. Usually any physician is designated as a CMO, and often the commander chooses to be a CMO. This decision is left to the commander of each mission. Because the CMOs become the arms, eyes, and ears of the Earth-based crew surgeon stationed in mission control, it is important for the crew surgeon to understand the capability of his or her CMOs and be able to communicate effectively. For this reason, the training of CMOs is usually provided personally by the crew surgeon and deputy crew surgeon assigned to the mission.

The initial training session is designated medical diagnostics and is usually held approximately 2 to 4 months before the mission. This session helps the CMOs use the diagnostic equipment in the SOMS kits to assess the health status of his patient. A variety of tools are used for this session, including audio- and videotapes, models, and patient contact. The CMOs are instructed in the use of the medical checklist from the SOMS kit and are familiarized with PMC procedures.

A second session focusing on therapeutics is held closer to launch. This session focuses on hands-on treatment experiences for procedures that are frequently needed, such as intramuscular injections. Emergency procedures that are not likely to be needed, but could be life saving, are also practiced. CMOs practice venipuncture, intravenous drug and fluid therapy, urinary catheterization, suturing, cricothyrotomy, intubation, and airway management. Although these procedures are usually done on inanimate practice models, some CMOs obtain additional experience practicing their procedures in the emergency room or operative theater environment. In addition, many CMOs develop their own proficiency and the confidence of their crewmembers by giving them required injections such as influenza vaccine, tetanus toxoid, or preflight test doses of promethazine. One further session is held with the NASA dental officer to acquaint the CMOs with common dental problems and the capabilities of the dental palate located in the SOMS kit.

During the weeks before flight, the entire crew gets an opportunity to again see the SOMS kits during bench review. Occasionally, a practice SOMS kit is requested for crew quarters so that the crew can review its capabilities and the medical checklist preflight.

Medical Equipment

The SOMS is the primary medical support system for shuttle flights. This system reflects knowledge obtained from 40 years of spaceflight experience, current medical thinking regarding medications, the expected frequency of common illnesses inflight, and the relatively short duration and ready return capability of shuttle missions. Although the kits provide the capability for advanced life support, this capability is limited in duration because of consumable constraints. Most of the medical capability is targeted to ambulatory care, first aid, and basic life support. Because medical knowledge, diagnostic capabilities, and medication usage are constantly evolving, the configuration control board periodically changes the kit configuration and contents to meet current needs (16).

The major components of the SOMS are the medication and bandage kit (MBK), emergency medical kit (EMK), shuttle emergency eyewash kit (SEE), medical accessory kit (MAK), contaminant clean-up kit (CCK), operational bioinstrumentation system (OBS), airway medical accessory kit (AMAK), resuscitator, radiation dosimeters, restraint system, and medical checklist. The checklist provides on-orbit direction to the CMOs for use of the kits. The MBK carries primarily oral medications, bandages, splints, and topical agents. The EMK carries supplies for parenteral administration of medications, intravenous lines, and advanced life support. The MAK contains specific items that may be needed for a specific mission based on the payload and mission objectives. If no items are needed for the mission, additional intravenous fluids are stowed in the MAK. The CCK contains goggles, chemically and biologically resistant gloves, masks, and disposal capability and is used to protect crewmembers from toxic, nontoxic, and biologic contaminants in the cabin. In case of ocular chemical exposure, simple irrigation or blinking into pooled saline or water applied to the orbital area can be done emergently. The SEE provides the capability to irrigate the eyes for a prolonged period using water from the shuttle system and venting the excess fluid into the shuttle waste collection system. The SEE provides a pair of self-contained goggles with appropriate connectors to integrate with the shuttle systems. The OBS provides the opportunity to downlink ECG data to the surgeon in mission control. The separate AMAK provides CMOs the opportunity to react to an airway or ventilation problem in a timely manner without having to dig through the other kits. It contains supplies for airway management, including endotrachial tubes, oral airways, nasal airways, end-tidal CO_2 monitor, and cricothyrotomy set, and interfaces with the SOMS resuscitator and shuttle oxygen system. A defibrillator has flown on specific flights but is not yet a consistent component of the SOMS.

Each crewmember may carry on personal medications in their LES or ACES. Occasionally, seasonal illness such as influenza or unexpected exposure to a communicable illness during quarantine can lead to a last-minute need for certain medications. The carry-on system provides the flexibility to get needed medications onboard for these occasions.

During the extended-duration orbiter program, longer shuttle missions of 16 to 18 days were accomplished in order to obtain additional data regarding human adaptation to spaceflight. Because the crew size was usually seven and the flights longer, additional medical supplies and improved diagnostic capabilities were warranted. To meet this need, the medical extended-duration orbiter pack was developed. This pack includes additional volume of medications found in the SOMS kits, additional medications not found in the SOMS kits, and added capabilities for diagnostics such as throat culture media.

Health Stabilization Program

The possibility that a preventable illness would delay a mission, impact mission success, or cause early termination of a mission led to the development of a preflight HSP for the space shuttle. The initial quarantine program was developed for the Apollo program, but the program was designed to protect those on Earth from possible lunar contamination. Following infectious illness problems on Apollo 7 and Apollo 13, an HSP was developed and has been in place continuously during the shuttle era. This program consists of health surveillance of individuals (primary contacts) that will come into contact with the crew, immunization for communicable illnesses, limited preflight quarantine of 7 days' duration, active evaluation of illness occurring in a primary contact of the crew, and medication prophylaxis of crewmembers, when indicated. Special primary areas are designated to limit general access to crews beginning 7 days before missions, and the crew is housed in crew quarters where the access, environment, and food preparation and safety can be adequately monitored. An education and health awareness program is also implemented that uses a combination of posters, videos, and badges. Since the initiation of the HSP, only a single flight (STS-36) has been delayed due to crewmember illness, and no communicable illness has caused mission impact on orbit. Several minor illnesses have occurred in crewmembers who did not have mission impact or delay a launch.

An additional aspect of the preflight health program involves the circadian shifting program. Because most shuttle launches occur on schedules that vary from the local 24-hour day, crewmembers would perform critical operations during their circadian nadir unless appropriate action was taken to reentrain their sleep–wake cycle with the operational schedule. Shuttle crews have the option of bright light therapy to help reentrain their circadian rhythm to accommodate the launch schedule, as well as to minimize the sleep deprivation that occurs with circadian shifting. This operational program has been in effect since STS-35 in 1990 and has proved to be helpful during preflight preparations.

Launch/Landing Medical Support

Medical support for shuttle launch includes the ascent and entry surgeon and biomedical engineers located in the Mission Control Center (MCC) at JSC, Kennedy Space Center (KSC) emergency medicine services coordinator and JSC deputy crew surgeon stationed in the firing room at KSC, triage and trauma team (which includes the crew surgeon deployed strategically near the launch site), and three to four helicopter teams staffed by physicians and paramedics. This team would handle any pad abort or a return-to-launch site abort. In addition, physicians and paramedics are deployed at each of the active transoceanic abort landing sites in Spain or Africa, and at Edwards Air Force Base in case of an abort-once-around. In the event of a shuttle abort landing, the crew surgeon and deputy crew surgeon serve on the crew recovery and rapid response team.

During nominal landing, the medical support resources are usually activated for the prime landing site or any planned backup sites. The crew transport vehicle (CTV) is stationed to mate with the orbiter through the white room and provide a working area to help with crew recovery and stabilization. After all the crew is recovered, the CTV transports them to the crew quarters or clinical areas for medical examinations, scientific data collection, and reunion with their families.

On-orbit Medical Support

Medical support during missions is conducted through the MCC at JSC in Houston. The crew surgeon or deputy crew surgeons staff the console with support from the multipurpose support room by biomedical engineers. In addition, the radiation monitoring team has access to the MCC through the surgeon console. The crew surgeon and deputy crew surgeon have the lead for crew health and safety issues and life sciences experiments and serve as the crew advocates for crew scheduling and exercise countermeasures. Staffing by the FSs is continuous during periods of crew activity, but may be accomplished remotely during single-shift missions when the crew is sleeping.

Each day the crew medical status is confirmed by a PMC conducted by the surgeons with the crew. Medical problems that require adjustment to the mission timeline or impact the mission are related to the flight director and management team. In the event that there is no mission impact, the PMC information is not forwarded to the control team. Private family conferences are also arranged for the crews at specified intervals.

The FSs in the MCC have considerable ability to monitor orbiter systems, including all the environmental systems. The surgeon console has databases for onboard toxicologic exposures, EVA prebreathes, crew medical records, crew timelines, mission profiles, and checklists.

Extravehicular Activity Operations

Other than launch and landing, the crew is at greatest risk during EVA. EVAs expose the crewmembers to the risk of extreme heat and cold, increased radiation, DCS, and the possibility of loss of suit pressure at vacuum. The current EVA suit is the extravehicular mobility unit (EMU), which provides 4.3 psig pressure of 100% oxygen. A liquid cooling and ventilation garment is used to provide thermal stability, and the gloves contain heaters, if needed. Most EVAs to date have been conducted using staged decompression from the shuttle, with the shuttle pressure reduced from 14.7 psig to 10.2 psig at least 24 hours before the EVA (Figure 24-9). To avoid the risk of DCS, the crewmembers prebreathe 100% oxygen for 1 hour before the initial depressurization and then for 40 to 75 minutes before depressing from 10.2 psig to the 4.3 psig EMU pressure. Aspirin prophylaxis is used before each depressurization. Although the original projections were that the total DCS rate would be approximately 20% and severe cases 3%, there have been no known cases of DCS of any

FIGURE 24-9 Astronaut Chris A. Hadfield stands on the portable foot restraint connected to the shuttle's robotic am (photo courtesy National Aeronautics and Space Administration).

severity during more than 60 shuttle-based EVAs, with total crew depress time of 400 hours. It has been postulated that microgravity reduces the formation risk of bubble nuclei, and Earth-based studies in Project ARGO (gas phase formation in microgravity) confirmed less risk with unweighted subjects than was originally projected. To enable EVAs from the 14.7 psig ISS airlock using the current suits, there has been considerable effort to reduce the current 4-hour in-suit prebreathe restriction by using mild exercise during the prebreathe to facilitate the off-gassing of nitrogen. Initial results obtained from Earth-based testing have been encouraging.

Each crew surgeon monitors EVAs meticulously and has the capability to monitor multiple EMU parameters, including oxygen, carbon dioxide, pressure, energy expenditure, and ECG. In addition, downlink of video and communication between the EVA crew and orbiter is usually available. Treatment options for DCS are somewhat limited, but most DCS associated with altitude or flying responds to repressurization to ground level. During shuttle-based EVA, the cabin can be repressurized from 10.2 psig to 14.7 psig. In addition, the EMU can provide an additional 4.3 psig. If a special bends treatment apparatus is used, the suit pressure can be increased to 8.0 psig for a total pressure of 22.7 psig. A problem in using the EMU for pressurization is that the suit limits medical access to the crewmember. It is possible to increase the shuttle cabin pressure to 15.8 psig, but a cabin pressure relief valve would open beyond that level. In the event that symptoms do not resolve with recompression or recur following treatment, the mission may be terminated.

INTERNATIONAL SPACE STATION MEDICAL OPERATIONS

With seven years of continuous human occupancy, the International Space Station (ISS) is a firm reality. These manned missions have initiated a planned 15-year life span of continual human presence aboard the largest orbiting laboratory in history. Aside from NASA, contributing organizations include the Russian space agency Rosaviokosmos, the Canadian Space Agency (CSA), the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), and the Italian Space Agency (ASI). Beyond basic membership in an international project, these IPs are active participants in planning, construction, control, and operation of the ISS. Once the multi-year assembly phase is complete, the ISS should comprise approximately 1,200 m^3 of pressurized volume, with a mass of approximately 420 metric tons. The ISS will orbit in an altitude range of 370 to 460 km at an orbital inclination of 51.6 degrees, similar to those of the former Russian Mir station. This will afford the station overflight of approximately 85% of the Earth's land mass and 95% of the Earth's population. Available electrical power of 110 kW and well-equipped investigative facilities will make the ISS a truly unique and productive orbiting space laboratory. Figure 24-10 depicts the ISS configuration following the STS-100 mission. For NASA and the U.S. space program, the ISS represents the following several major points of transition:

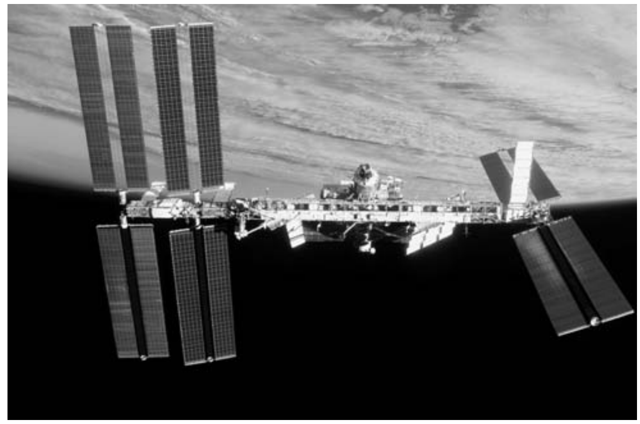


FIGURE 24-10 International Space Station as photographed during the STS-100 mission.

- Shift from primarily short-duration shuttle missions to include long-duration flight
- Permanent human presence in space
- Multilingual/multicultural operating environment
- Multiple operational control and monitoring centers
- Multiple launch and landing sites
- Complex continual program of assembly and maintenance

The first two points are not new paradigms for Russia, with a rich and lengthy history of successful long-duration spaceflight aboard the Salyut series of stations and the Mir station. All other points apply equally to all ISS participants and present similar operating challenges. Along with these, many relevant conditions and practices vary among the participants. These include basic standards of medical care, approach to human life sciences, handling of medical data, crew medical training, and medical support infrastructure. Multilateral medical operations groups were formed early in the ISS planning stages to achieve common ground in approaching medical support for international crews. The necessary products of these groups have included joint medical requirements for ISS operation and medical capability, common medical standards for crew selection and certification, common environmental parameters and toxicologic limitations, and an integrated implementation plan to coordinate medical support across international lines and between control centers (17,18). In most of these cases, common guidelines have been developed that are accepted and subscribed to by all participants; beyond these, participants may exercise some additional latitude with their crewmembers based on their particular epidemiology, experience base, or national health standards.

The overall formation and implementation of medical support for the ISS is based on the following fundamental assumptions:

- All crewmembers will function as an integrated crew during all mission phases.

- All crewmembers will have equal access to preventive, diagnostic, and therapeutic capabilities aboard the ISS, as well as to ground-based expertise and consultant networks.
- Mission Control Center Houston (MCC-Houston) will serve as the lead control center; however, MCC-Moscow will remain active in the control and support of primarily Russian elements and hardware.
- Commensurate with the increase in crew complement from other IPs, additional medical support may be added from other MCCs.
- Medical data from ISS crewmembers will be handled as private and confidential following common guidelines.
- Crew size is three until near assembly completed, when an additional habitation module and environmental support capability will enable a crew of six.
- The official ISS working language is English; however, Russian segment operations will be conducted in Russian, and selected private medical and family communication will be in the crewmember's native language.
- The system of measurement is metric

Across the multinational lines, the medical operations support structure maintains overall responsibility for all aspects of crew health and safety. This includes medical certification and training, response to medical events, environmental monitoring, inflight countermeasures, and overall evolution of medical support as circumstances dictate. The medical operations purview therefore includes subsystems, with both hardware and operational implementation and oversight, to protect crews accordingly from the deleterious effects of spaceflight. An important premise is that because a given crew's space mission experience is not limited to the inflight phase, medical support must be provided in all mission phases, including preflight, inflight, and postflight. For example, physical training begins with a preflight assessment and prescribed exercise program, continues with inflight physical countermeasures and exercise, and culminates with supervised and monitored postflight physical rehabilitation. Medical operations operates in a continuum over various mission phases to optimize crew performance, and to ensure restoration to preflight levels of health.

The following sections describe specific aspects of medical support for the ISS.

Bioenvironmental Parameters of the International Space Station

Like the Shuttle and the Mir station, the ISS is to maintain a shirtsleeve environment that allows crews to live and work freely and accommodate a range of materials and life science experiments. Cabin atmosphere will be maintained at sea-level equivalent, with an oxygen/nitrogen mix. Table 24-2 depicts ranges of common bioenvironmental monitoring parameters, available to ground personnel through telemetry display.

Because crewmembers will inhabit the ISS for many months at a time, chronic low-level exposures to potentially adverse factors take on an increased health emphasis as compared with shorter-duration flights. Along with dynamic atmospheric monitoring, periodic sampling of air, galley water, and surfaces will ensure that limits of chemical contaminants, particulates, and microbial species are not exceeded. As noted in the preceding text, these limits derive from a set of joint guidelines developed and accepted by all IPs. Most of these samples will be returned for ground analysis, although limited capability for assessment of water quality and certain toxic atmospheric constituents (carbon monoxide and other pyrolysis products) is available on board. In addition, ambient noise levels will be periodically assayed using onboard acoustic measuring devices, and periodic crew audiometry tests conducted using a laptop based hearing assessment. Such measurements will characterize the ISS acoustic environment to quantify crew exposures, identify and correct noise-producing hardware assemblies, and guide the use of hearing protection.

TABLE 24-2

International Space Station Bioenvironmental Parameters

Pressure (mm Hg/psia)	740–780/14.2–14.9
Oxygen partial pressure (mm Hg/psia)	146–178/2.82–3.44
Temperature (°C)	18–29.5
Dew point	≤14°C
Carbon dioxide (mm Hg)	5.3 or less averaged over 5 d (peak 7.6)

psia, pounds per square inch absolute.

The spaceflight environment also involves exposure to levels of radiation well beyond terrestrial norms. Quantifying crew exposure and the overall station environment requires a multifaceted approach to monitoring. Sources include geomagnetically trapped radiation, galactic cosmic rays (GCRs), and solar wind and occasional solar particle events. Geomagnetically trapped particles (Van Allen radiation) consist primarily of lower energy protons and electrons. The greater fraction of crew exposure is due to passes through the South Atlantic Anomaly, a region characterized by a large flux of trapped protons at an altitude much lower than the bulk of the Van Allen belts. GCRs consist of approximately 87% high-energy protons, 12% heavier α particles, and approximately 1% heavy ionic species such as iron (19). Although flux is low, particle energies are high, making shielding problematic. Solar particle events are episodic bursts of moderate-energy protons and electrons; the major hazard stems from the very high particle flux associated with these events. In addition, neutrons are generated from primary interactions of high-energy particles with spacecraft structural elements.

Accumulated dose is monitored over time and applied against both mission and career limits. These limits derive from advisory groups outside of NASA and make use of analogous exposure data (terrestrial radiation workers,

TABLE 24-3

Radiation Career Dose Limits in Centisieverts (3% Excess Cancer Mortality Risk)

Age	Male	Female
25	70	40
35	100	60
45	150	90
55	300	170

1 Sv = 100 rem.

atomic bomb survivors), using the resulting lifetime risk of cancer as a standard metric. NASA limits are based on recommendations from the National Council of Radiation Protection and Measurements and equate to a 3% increase in excess lifetime cancer mortality. Career limits are age and gender weighted, and have recently been revised to reflect updated analysis of analog data and improved understanding of cancer risk modes (20–22). Current NASA operational limits for low Earth orbit are shown in Table 24-3.

Daily radiation doses aboard ISS is dependent on altitude and relation to solar cycle; an exposure range from 5 to 20 cSv may be expected for a 4- to 6-month mission. It is an administrative and operational policy to maintain radiation levels as low as possible, with the philosophy of never approaching the "legal limits." This influences mission design and duration, and requires a comprehensive monitoring program; it is evident that accumulated radiation dose is a major factor in the number and duration of flights in a crewmember's career. All crewmembers will wear a personal dosimeter at all times while on orbit to be analyzed postflight. The ISS habitable volume will also be assayed using deployable radiation area monitors, which will be returned on a cycle roughly coinciding with a crew increment. In addition, a tissue equivalent proportional counter and intra- and extravehicular charged particle detector/spectrometer serve to monitor GCR.

Crew Medical Training

Just as launching mass to orbit is severely constrained, generic crew training time before flight is a limited commodity. For ISS crewmembers, added training challenges include periodic overseas travel with major portions of training at JSC in Houston and the Gagarin Cosmonaut Training Center in Star City, Russia, with shorter periods at other IP centers. Along with this, training is given in both English and Russian, requiring at least bilingual language abilities. As such, ISS crew training inherently involves added potential for stress and fatigue compared with prior manned spaceflight. One role of medical operations is to monitor the overall training timeline and, if necessary, intervene to avoid launching an exhausted crew.

Medical training includes that required to use diagnostic and therapeutic hardware, conduct medical assessments, and perform environmental monitoring and microgravity countermeasures performance and assessment. The suite of medical equipment available is multinational in origin, and it is the responsibility of each IP to develop and conduct crew and ground support personnel training on their individual medical systems and payloads. As such, this must be carefully coordinated into an integrated training plan. Basic medical training will be available for all crewmembers; however, more advanced paramedic-type training will be provided for two designated CMOs for each ISS flight increment. One or two crewmembers also will be trained as environmental control and life support (ECLSS) specialists to perform environmental monitoring activities. Typically, ISS CMOs and ECLSS crewmembers will be trained by mission-assigned FSs and biomedical engineers who support the mission from the flight control centers. This capitalizes on the understanding between trainers and crew, and provides an important continuity link during mission contingencies.

Table 24-4 shows the overall breakdown of training hours allocated to NASA medical operations for one of the early ISS expeditions. Table 24-5 shows the equivalent for Russian medical training. Together they form the basis of medical preparation for ISS crew capabilities and operation, which begins 18 months before scheduled launch.

Significantly, the medical checklist, the basic field manual used by CMOs for rendering medical care during training and inflight, is a bilingual product with English and Russian on facing pages. In addition, dual-language English-Russian training material is being developed to aid crewmembers in learning systems as efficiently as possible. Although there are other languages represented among the IP crewmembers, a practical fact is that most of these crewmembers are proficient in English, and most medical hardware will be of Russian and U.S. origin.

It is a daunting task to train crewmembers without professional clinical backgrounds to proficiency within the timeline. However, this represents a best-fit approach given the medical risk assessments and the resources available. When possible, the training template is supplemented by refresher experiences, and supervised hospital and ambulance experience is occasionally afforded. As the crew size increases to six individuals, the relative risk may shift more toward the recommended inclusion of a physician on as many increments as possible to best ensure mission success.

Medical Equipment

Much has been learned over 40 years of spaceflight with regard to medical problems associated with this working environment. In parallel, terrestrial medical standards and technology have progressed to a point where what was once considered tertiary care is now expected field medical capability. These factors have led to a new minimum level of inflight medical intervention and care, which includes basic first aid, routine care of minor medical and surgical problems, basic life support, limited advanced life support, and stabilization and transport of seriously ill

TABLE 24-4

Sample Template of U.S. National Aeronautics and Space Administration (NASA) Medical Training for International Space Station (ISS) Crewmembers

Class or Practical Session	*Crew*	*Time*	*Time Before Launch*
ISS space medicine overview	Entire crew	0.5 hr	18 mo
CHeCS overview	Entire crew	2 hr	18 mo
Cross-cultural factors	US only	3 hr	18 mo
Psychological support familiarization	US only	1 hr	18 mo
Countermeasures system operations 1	Entire crew	2 hr	12 mo
Countermeasures system operations 2	Entire crew	2 hr	12 mo
Toxicology overview	Entire crew	1 hr	12 mo
EHS microbiology operations and interpretation	ECLSS	2 hr	12 mo
EHS water quality operations	ECLSS	2 hr	12 mo
EHS toxicology operations	ECLSS	1 hr	12 mo
EHS radiation operations	ECLSS	1.5hr	12 mo
Carbon dioxide exposure training	Entire crew	1 hr	12 mo
Psychological factors 1	US only	2 hr	10 mo
Dental procedures	CMOs	1 hr	8 mo
ISS medical diagnostics 1	CMOs	3 hr	8 mo
ISS medical diagnostics 2	CMOs	2 hr	8 mo
ISS medical therapeutics 1	CMOs	3 hr	8 mo
ISS medical therapeutics 2	CMOs	3 hr	6 mo
ACLS equipment	CMOs	3 hr	6 mo
ACLS pharmacology	CMOs	3 hr	6 mo
ACLS protocols 1	CMOs	2 hr	4 mo
ACLS protocols 2	CMOs	2 hr	4 mo
Cardiopulmonary resuscitation	Entire crew	2 hr	4 mo
Psychiatric issues	US only	2 hr	4 mo
Countermeasures system evaluation operations	CMOs	3 hr	4 mo
Neurocognitive assessment software	US only	1 hr	4 mo
Countermeasures system maintenance	OOM	2.5 hr	4 mo
EHS Preventive and Corrective	OOM	1 hr	4 mo
Maintenance	—	—	—
ACLS "megacode" practical exercise	Entire crew	3 hr	3 mo
Psychological factors 2	US only	2 hr	1 mo
Medical refresher	Entire crew	1 hr	2 wk
CMO computer-based training	CMOs	1 hr/mo	Onboard
CHeCS health maintenance system contingency drill	Entire crew	1 hr	Onboard

CHeCS, crew health care system; ACLS, Advanced cardiac life support; CMO, crew medical officer task allocation; ECLSS, environmental control and life support system task allocation; EHS, environmental health system; OOM, on-orbit maintenance task allocation.

or injured crewmembers. New requirements have driven the inclusion of cardiac electrical defibrillation, physiologic monitoring, and automated ventilation capabilities for the ISS, representing a major leap in medical capabilities from prior spaceflight efforts.

In the years of ISS assembly, the onboard medical inventory will consist of both Russian and U.S. supplied diagnostic and therapeutic hardware and medications. These are coordinated by the multilateral group and known as the integrated medical system (IMedS). This approach allows for complementary capabilities and familiar formularies to be available to these organizations. It is anticipated that supplemental equipment and medications will become available as other participant agencies are represented in the crew and as experience is accrued to refine selection. To perform optimally, the IMedS must avoid undue duplication and at the same time provide some level of redundancy, with procedures developed to apply all resources available to a given medical event. As noted, a bilingual English-Russian medical guide is available to the CMOs. Familiarity of the entire system among both crewmembers and ground support personnel is crucial to successful utilization. To bolster crew proficiency and provide refresher training, at least one inflight practice medical drill is scheduled for each increment.

Table 24-6 lists the general Russian contribution to the onboard medical inventory, to be stored in the service module. A basic approach is to package medications and supplies in problem-oriented kits for crew convenience. Most of these are compact enough that they can be easily

TABLE 24-5

Sample Template of Russian/Russian Space Agency Medical Training for International Space Station (ISS) Crewmembers

Class or Practical Session	*Crew*	*Time (hr)*	*Session Type*
1. Medical diagnostics, crew health care system			
Principles and methods of rendering first aid inspaceflight	Entire crew	2	Lecture
Instruction on diagnosing conditions and rendering self and mutual aid using the flight pharmacy and medical kits	Entire crew	2	Practical
Stomatology	Russian only	1	Practical
Epidemiology	Russian only	1	Lecture
2. Physical training			
Theoretic principles of cosmonaut physical training	Entire crew	2	Lecture
Onboard physical deconditioning countermeasures			
3. Technical training			
Medical monitoring hardware gamma system	Entire crew	2	Lecture/Practical
Medical monitoring hardware: mass measurement, urinalysis, mini centrifuge, blood chemistry analyzer, blood pressure monitor	Entire crew	2	Lecture/Practical
Medical monitoring hardware: laboratory refrigerator, large centrifuge	Entire crew	0.5	Practical
α-11 biomedical monitoring apparatus	Entire crew	0.5	Practical
Physical countermeasure items: cycle ergometer, LBNP "Chibis" device, Myostimulator "Tonus" device	Entire crew	2	Lecture/Practical
Layout of the onboard medical support system	Entire crew	1	Practical
4. Biomedical section of flight program			
Soyuz transport vehicle and ISS Russian segment (RS) medical support system			
Arrangement of spaceflight medical support: overview	Entire crew	1-2	Lecture
ISS RS medical monitoring system	Russian only	2	Lecture
Countermeasures system in long-duration spaceflight	Entire crew	1	Lecture/Practical
Sanitary and hygiene facilities 1	Entire crew	2	Lecture/Practical
Sanitary and hygiene facilities 2	Entire crew	1	Practical
Onboard food system	Entire crew	2	Lecture/Practical
Radiation safety	Entire crew	1	Lecture/Practical
Countermeasures hardware: kentaver, penguin suits, brazlet, electromyostimulation, pharmacology	Entire crew	2	Practical
Hearing protection set	Entire crew	0.3	Practical
Onboard food ration taste test	Entire crew	4	Taste testing
Onboard menu trial (crewmember substitutes meals with flight-like food rations for a 6-day menu cycle)	Entire crew		Meal substitution
Onboard noise level measurement	Russian only	0.5	Practical
Medical monitoring			
Study of cardiac bioelectric activity	Entire crew	1	Practical
24-hour ECG recording	Entire crew	1	Practical
Physical conditioning level evaluation (treadmill test)	Entire crew	1	Practical
Evaluation of orthostatic tolerance during LBNP	Entire crew	2	Practical
Physical training level evaluation (cycle ergometer)	Entire crew	1.25	Practical
Evaluation of arm musculature	Entire crew	0.5	Practical
Calf volume measurement	Entire crew	0.25	Practical
Body mass measurement	Entire crew	0.5	Practical
Biochemical urine analysis	Entire crew	1	Practical
Hematocrit	Entire crew	1	Practical
Reflotron biochemical blood analyzer	Entire crew	2	Practical
ECG at rest	Entire crew	1	Practical
Microbiologic environmental monitoring	Entire crew	2	Practical
Sanitary-epidemiologic monitoring	Entire crew	0.25	Practical
Trace gas environmental contaminants	Entire crew	0.25	Practical
Refresher training	Entire crew	2	Lecture/Practical
Test on biomedical section of flight program	Entire crew	2	Exam

ISS, International Space Station; LBNP, lower body negative pressure; ECG, electrocardiogram.

TABLE 24-6

Russian Medical System

Therapeutic kits	
	On-board medications/supplies
	Splint kit
	Cardiovascular medicine kit
	Gastrointestinal and urology kit
	Psychotropic medications
	Aseptic medicine kit
	Medicine for burns and injuries
	Dressing kit
	Anti-inflammatory medicine kits
	Prophylactic medicine kits
	Ointment kit
	"Aspirin/analgesic" kit
	Emergency kits
	Otorhinologic and ophthalmologic kit
	Stomatologic (dental) kit
Medical monitoring and diagnosis	
	"Reflotron" clinical chemistry analyzer
	Minicentrifuge for hematocrit measurement
	"Urolux" clinical urine analyzer
	"Plasma" clinical centrifuge and refrigerator set
	"Gamma" multichannel biomedical monitoring system
	24-hour electrocardiogram monitor
	Automatic blood pressure monitor
	Body mass measurement device
	Calf volume measurement device
Countermeasures items	
	Cycle ergometer
	Resistive bungees
	Loading suits
	Lower body negative pressure device
	Electromyostimulator
	Thigh cuffs for attenuation of fluid shifts
Environmental monitoring items	
	Surface sampling kit
	Atmospheric gas sampler
	Microbial air sampler
	Radiation dosimeters, individual
	Radiation dosimeters, area

TABLE 24-7

International Space Station Crew Health Care System

Health maintenance system (HMS)	
	Advanced life support pack
	Ambulatory medical pack
	Cardiac defibrillator/monitor
	Central supplies kit
	Crew contamination protection kit
	Crew medical restraint system
	Respiratory support pack
Countermeasures system	
	Blood pressure/electrocardiogram monitor (shared with HMS)
	Cycle ergometer/vibration isolation device
	Metabolic gas monitor
	Resistive exercise device
	Treadmill/vibration isolation device
Environmental health system	
	Charged particle directional spectrometer (intravehicular)
	Charged particle directional spectrometer (extravehicular)
	Compound specific analyzer: combustion products
	Compound specific analyzer: hydrazine
	Dosimetry package (radiation)
	Fungal spore sampler
	Ion selective electrode assembly (water analysis)
	Medical equipment computer
	Microbial air sampler
	Microscope/camera
	Spectrophotometer (water)
	Surface sampler kit
	Tissue equivalent proportional counter (radiation)
	Total organic carbon analyzer (water analysis)
	Volatile organic analyzer
	Water microbiology kit
	Water sampler and archiver

prepared and stowed on any transport of opportunity, such as the Soyuz crew transport, Progress freighter, or shuttle to enable rapid critical resupply. Because logistics is a particular challenge due to medication shelf life and crew use, this is a desirable feature.

NASA-supplied equipment, known as the crew health care system (CHeCS), will be based in the U.S. laboratory and habitation modules. Similar to Russian medical items, the CHeCS is further broken down along functional lines into the following subsystems: health maintenance system (HMS) containing medical diagnostic and therapeutic hardware and medications; environmental health system (EHS), containing atmosphere, water, and microbial analysis equipment; and the countermeasures system, which includes equipment for performing routine physical exercise and physiologic monitoring of fitness. Table 24-7 summarizes the CHeCS.

Health Stabilization Program

Crewmembers may launch to the ISS on either the U.S. shuttle or the Russian Soyuz. In each case, an HSP is in effect to control access to crewmembers before launch and minimize the risk of infectious disease. Crewmembers launching on the shuttle are placed into quarantine at JSC 7 days before launch and remain isolated as they transition to the launch site at KSC 3 to 4 days before launch, regardless of whether remaining on the shuttle or bound for the ISS. Only adults who have been medically screened may be in contact with crewmembers during this time. Crewmembers launching on the Russian Soyuz undergo similar measures, including a premission quarantine at the Gagarin Cosmonaut Training Center in Star City and continuing at the Baikonur

Cosmodrome launch site in Kazakhstan. The combination of preflight crew medical examinations and HSP has served to effectively control infectious disorders during spaceflight for many years.

Although long-duration spaceflight is known to induce some potentially adverse *in vitro* effects on the immune system, there does not appear to be any increase in clinically recognized infectious disease for those freshly returned from spaceflight. For this reason, an HSP is not formally in effect in the postlanding period. However, access to crewmembers is limited to afford optimal crew rest, rehabilitation, and postflight examination activities.

Preflight Medical Testing/Certification

Candidates for ISS mission increments are drawn from a pool of astronaut trainees who have passed initial medical selection and annual medical evaluations. Each IP endorsing a crewmember candidate to the ISS will conduct the initial medical evaluation and certification requirements according to common standards. Once accepted by the multilateral medical board, the crewmember enters an increment-specific training flow, which includes periodic medical and fitness assessments. These are matched by postflight medical assessments and are summarized in Table 24-8. Aside from screening for any occult disease processes, these assessments serve to guide countermeasures implementation, identify risks for an individual before prolonged exposure to microgravity, and assess the effects of the flight for the individual by combining and comparing preflight and postflight results. These help to guide rehabilitation efforts and assess candidacy for future long-duration assignments.

Some difficulties arise in implementing these evaluations. Although the requirements comprise jointly accepted standards, analysis and performance methods differ for some tests across the partner nations. This makes results potentially more difficult to compare. Crew travel before and after flight may further compromise standardization of testing due to evaluations being performed using different laboratories and equipment. For example, bone densitometry assessed by DEXA is best measured using the same apparatus, requiring the crewmember to be in that setting for the scheduled test. It is clear that some flexibility is required in implementing this examination schedule. Finally, differing epidemiology among IP populations might lead individual partner nations to perform additional tests outside the core requirements.

On-orbit Medical Support

Medical support for a long-duration space mission begins well before and ends well after flight. However, the flight period of the mission demands the highest level of attention and coordination by all members of the medical operations team, generally led by the mission-assigned FS. The periodic assessment of the health of crew and their supportive environment provide a basis of approval for continuation of the flight. Inflight environmental monitoring, performance of countermeasures, and inflight medical assessments are scheduled by and coordinated with the ground medical operations team. In the operating environment of the ISS, this necessarily involves real-time communication between multiple centers to administer a coordinated program. Figure 24-11 depicts the general ground medical support infrastructure for the ISS; the lead MCC for ISS is at JSC in Houston. In this global setting, the role of communication and language differences cannot be overemphasized. Mechanisms and processes are in place to afford timely communication and translation services as required for safe operations. However, opportunities for miscommunication, both inflight and on the ground, are inherently increased. Daily joint production of a comprehensive biomedical report serves to consolidate all information relevant to medical operations, and to further synchronize the understanding of the operating environment for all participating centers.

In addition to a dedicated lead mission FS and biomedical engineer, any IP with crewmembers flying onboard may have a participating FS accommodated in the lead flight control center. FSs and biomedical engineers serve as formal flight controllers in the MCC and must be trained to an appropriate level of proficiency. The FS enforces aeromedical flight rules, provides inputs to all crew activities and planning, and provides immediate response to medical situations arising during flight. The FS has authority and responsibility to intervene appropriately in medical and environmental emergencies, up to recommending termination of the mission. Aside from standing ready to assist in delivery of medical care, medical operations personnel must serve as systems and information managers commensurate with other flight control positions. Figure 24-12 depicts information managed by the medical operations team in MCC-Houston; a complementary set of information from Russian medical resources is available to personnel in MCC-Moscow. Results and information are shared between MCCs through dedicated electronic voice and data links. Added to this are results of ground analysis from returned samples of water, atmospheric constituents, and surface microbiology.

For the actual delivery of medical care to the crew, responsibility is shared by the trained CMOs inflight and the supporting FSs. A weekly PMC between individual crewmembers and their FSs affords the opportunity to confidentially assess overall state of health and discuss chronic and minor health problems and remediation. The importance of truly private and candid communications between crew and FSs cannot be overemphasized; this is the medium for the basic and time-honored physician–patient relationship. As might be expected, during the first few weeks such conferences are oriented largely toward physiologic adaptation to microgravity and performance of countermeasures. In the event of a medical contingency, a PMC may be called at any time and, as bandwidth permits, might involve video imaging. The on-duty FS is the primary source of time-critical decisions. However, an extensive network of consultants is available to control centers in Moscow and Houston for rapid access; these include specialists in radiation, toxicology, nutrition, human factors, and relevant clinical subspecialties.

TABLE 24-8

Preflight and Postflight Medical Evaluation Requirements: Long-Duration Flight (More than 30 Days)

Examination	*Time in Relation to Flight* L − 180	L − 90	L − 30	L − 7	L − 2	R + 0	R + 2	R + 3	R + 5 − 7	R + 10	R + 15	R + 20	R + 30
Cardiovascular/ cardiopulmonary													
Electrocardiogram resting	√		√			√	√						
24-hr ambulatory	√												
Treadmill	√		√										
Operational tilt test			√			√		√		√			
Pulmonary function tests			√				√						
Dental examination		√											
Dental radiographs			√[a]										
Imaging													
Abdominal ultrasonography		√											
Pelvic ultrasonography			√[b]										
Laboratory													
Blood			√	√		√	√					√[c]	√[c]
Radiation		√[a]								√[a]			
Biodosimetry													
Purified protein derivative (PPD) skin test			√										
Urine			√			√							
Microbiologic assessments			√	√		√	√						
Musculoskeletal													
Aerobic capacity	√												
Aerobic submaximal test	√		√						√		√		√
Anthropometry Measurements			√			√	√						
FASTEX agility test	√		√						√		√		√
Functional fitness test	√		√						√		√		√
LIDO isokinetic test	√		√						√		√		√
Standard DEXA protocol			√						√				
Strength measurements			√										
Neurologic evaluation													
Functional neurologic Assessment			√				√			√			√[c]
Nutritional assessment													
Body composition (DEXA)	√												
Body weight	√			√									
Bone densitometry (DEXA)	√												
Clinical nutritionist Assessment	√												
Ophthalmology			√				√						√[c]
Otolaryngology													
Audiogram			√				√						
Specialist examination			√[c]				√[c]						
Physical examination		Full	Brief	Brief	Full	Full			Full		Brief	Full	
Psychiatric/psychological evaluation													
Specialist evaluation	√	√	√										
Neurocognitive testing	√		√										

L − 180, 180 days before launch; R + 2, 2 days after reentry.
DEXA, dual-energy x-ray absorptiometry.
[a]Test frequency may vary.
[b]Females only.
[c]Performed only if clinically indicated.

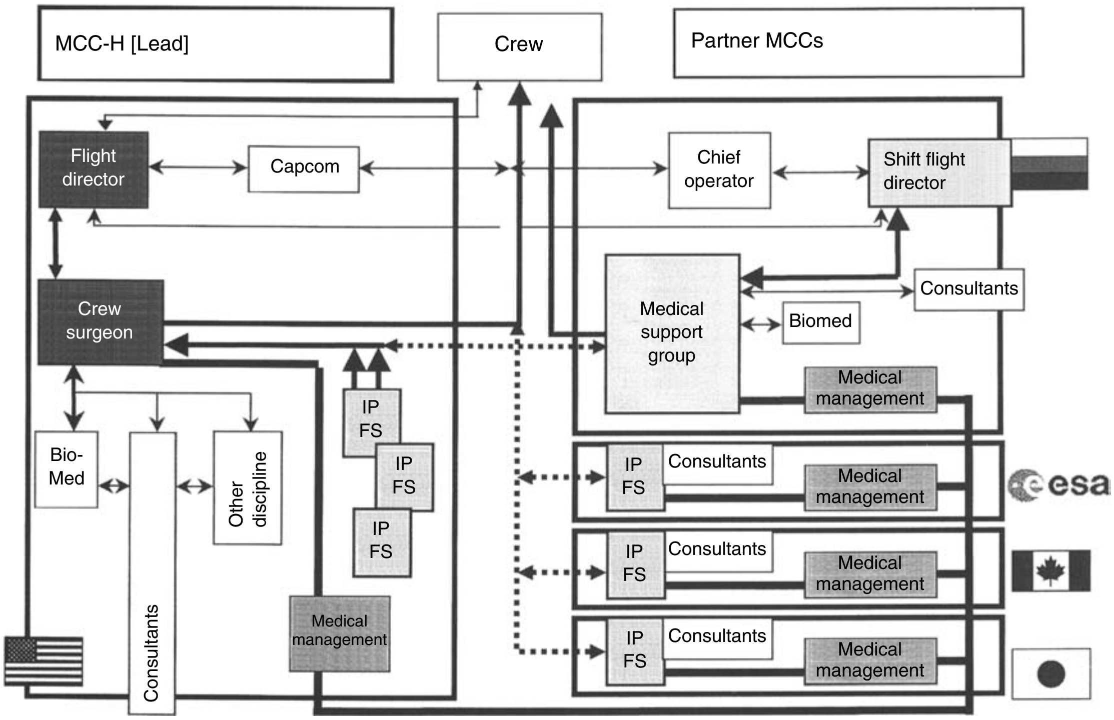


FIGURE 24-11 General multinational medical support infrastructure for the International Space Station.

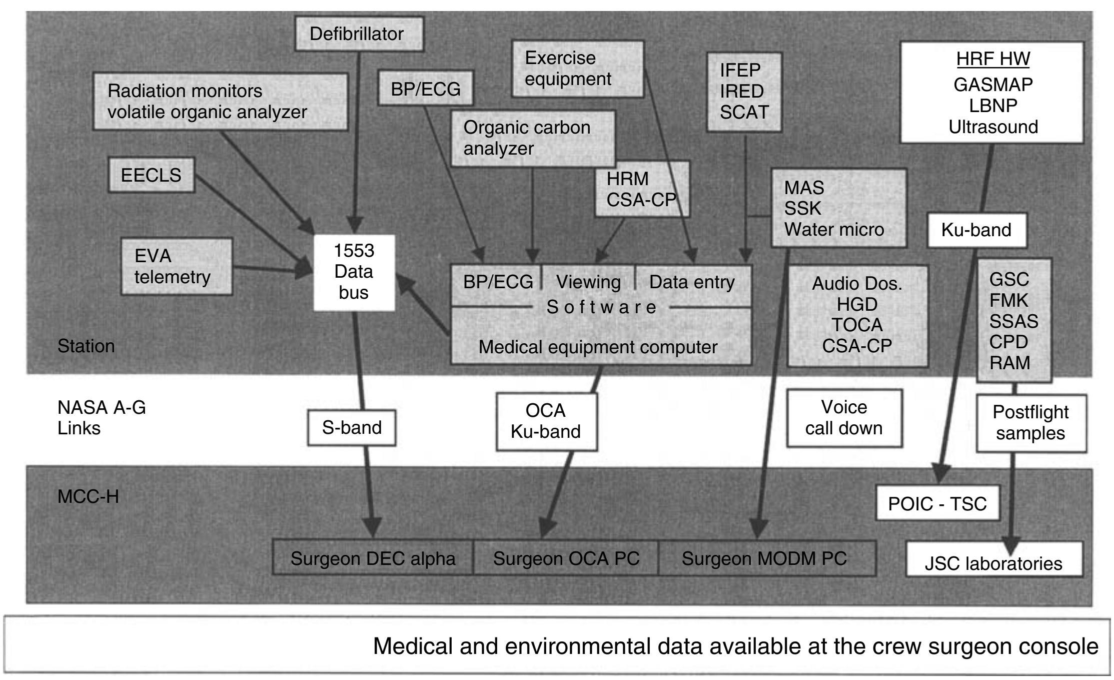


FIGURE 24-12 Biomedical and environmental data available at the surgeon's console, Mission Control Center, Houston. BP, blood pressure; ECG, electrocardiography; IFEP, in-flight examination program; IRED, resistive exercise device; SCAT, space cognitive assessment tool; HRF, human research facility; GASMAP, gas analysis system for metabolic analysis and physiology; LBNP, lower body negative pressure; ECLSS, environmental control and life support system; HRM, heart rate monitor; CSA-CP, compound analyzer-combustion products; MAS, microbial air sampler; SSK, surface sampler kit; TOCA, total organic carbon analyzer; GSC, gas sample container; FMK, formaldehyde monitoring kit; SSAS, solid sorbent air sampler; CPD, crew passive dosimeter; RAM, radiation area monitor; NASA A-G, National Aeronautics and Space Administration air-to-ground; OCA, orbiter communications adapter; POIC, Payload Operations Integration Center; MCC, Mission Control Center; JSC, Johnson Space Center.

In addition, biomedical engineers staff the MCCs full time to support use of medical hardware and implementation of procedures.

Despite an extensive ground support network, a certain degree of crew autonomy in responding to all medical events is required. Two-way communications with the ground is not full time and will depend on assembly phase and orientation of the ISS with respect to its orbital track. In some attitudes, structural impingement of antennas will impair ground communication and telemetry. After assembly is completed, will not be available for the entirety of each 90-minute orbit, and communications loss due to equipment malfunction is always a possibility. An ISS crew must therefore be capable of a fairly complete initial response to critical medical events and be trained and equipped accordingly. Development and field testing of a mature autonomous capability should be considered an expected product of the ISS, necessary for future exploration-class missions.

On-orbit Psychological Support

In discussing psychological support for long-duration spaceflight, it is necessary to understand the "psychological surround" associated with a typical ISS mission. The preflight period is characterized by an intensive and frequently fatiguing schedule of cognitive and physical training beginning a minimum of two years prior to flight; three to four years is more typical. Periodic international travel across multiple time zones adds to fatigue and implies separation from family and other usual sources of social support. Absorbing material in a secondary language in lecture and practical sessions compounds with cultural differences in adding to preflight stress. Typically the training schedule intensifies as launch draws near, potentially precluding the launch of a well-rested crew. Once the hazardous launch and rendezvous activities are completed, the ISS work environment is characterized by cramped surroundings, intensive work schedules, deleterious effects of microgravity, high ambient noise levels, nonfamiliar food and hygiene methods, general sensory deprivation, separation from family, and social isolation. Workers in this setting are highly visible, and implications of mistakes are far reaching. Communication and coordination with multiple ground centers in at least two languages adds further to stress. These are the baseline conditions, independent of major hardware malfunctions or crewmember illness. Following landing, the physiologic stress of being reintroduced to Earth's gravity is added to a formal program of physical rehabilitation, technical debriefs, and public appearances. Integrating back into the family and social setting also requires special attention.

The overall goal of psychological support is to address these potential stress factors proactively and reactively to best support long-duration space flyers and optimize their performance. This support must begin as the crew is assigned. Training activities include crew dynamics and cross-cultural factors, and special needs and requests of crewmembers are assessed on an individual basis. Education of crew families on the implications of long-duration spaceflight is also made available. Choices of items to be included in a limited crew personal inventory available on the ISS, including books, music, recreational videos, and pictures, are made preflight. Dynamics and interactions of each crew are assessed during the course of training activities, and recommendations are made by the behavioral health and performance group personnel to optimize general crew communication and effectiveness.

During flight, the behavioral health and performance group facilitates services such as private family conferences with crewmembers and crew mail, native language news broadcasts, and other social and recreational activities. Confidential family communication is a logical and fundamental need, allowing crewmembers to remain active participants in family activities and decisions. A regularly scheduled private psychological conference affords each crewmember an opportunity to discuss further requests or concerns with a ground specialist. Although information resulting from such conferences remains private, the specialist can make recommendations to the crewmember, FS, or flight control team as appropriate. In addition, a neurocognitive assessment tool in the form of a computer-based questionnaire is available on-orbit should such concern arise, for instance, following a toxic or adverse metabolic event or primary behavioral symptoms being noted in a crewmember. Baseline data are obtained preflight.

One of the more vital roles of the behavioral health and performance group is to define and enforce the work-rest requirements. Unlike the "sprint" mentality of the shuttle world, a work pace that can be realistically maintained for several months must be established and followed. Deviations will occasionally require more intensive workloads, but periods of time off and crew rest must offset these. The nominal crew workweek comprises 5.5 days, with 1.5 days each week reserved for station "housekeeping" activities and off-duty time. The crew workday is broken down roughly as follows:

8.5 hours	Crew sleep
1.5 hours	Postsleep activities (breakfast, hygiene)
0.5 hour	Planning and coordination
8.0 hours	System and payload operations
1.0 hour	Mid-day meal
2.5 hours	Exercise (including cleanup and equipment setup)
2.0 hours	Presleep activities (dinner, hygiene)

Frequently mission requirements and payload operations preclude rigid adherence to this schedule; however, this provides a guideline to mission planners to appropriately task the crew and avoid fatigue. Scheduling off-duty time for such recreational activities as amateur radio contacts, reading, and informal Earth viewing is a must.

The behavioral health and performance group works closely with the FS in developing an integrated approach to crew well-being. In particular, relative contributions of physiologic adaptation and environmental stressors to the psychological state, such as ambient noise levels and air quality, can be actively addressed with recommendations to the flight control team. This relationship continues into the postflight period to ensure successful and complete crew rehabilitation.

Inflight Countermeasures

A broad-based program of countermeasures is provided on the ISS to counteract the adverse effects of prolonged microgravity as described in an earlier section of this chapter. The cornerstone is physical exercise, oriented toward stemming the loss of bone density, muscle atrophy, and cardiovascular deconditioning known to occur in weightlessness. Owing to overhead of equipment setup and cleanup, the requirement for 2.5 hours of scheduled exercise time each day equates to an actual exercise time of 1.5 hours, considered a best estimate of the balance between required physical loading and productive crew work. Both aerobic and resistive exercise is afforded using cycle ergometers, a treadmill, and a dedicated resistive exercise device (Figure 24-13). Ancillary items such as handgrip exercisers and bungee cords augment these devices and serve as backups in case of equipment failure. A requirement to maintain a pristine environment on ISS for microgravity science investigations (vibrations limited to 10^{-6} G) and structural loading limitations severely constrains design of exercise hardware, necessitating sophisticated isolation mechanisms.

Each crewmember will follow an individual exercise prescription based on preflight data, conditioning, and prior flight experience, when applicable. Dedicated mission-assigned physical trainers monitor daily exercise through recorded heart rate data synchronized with treadmill and cycle ergometer data, which is periodically downlinked as part of crew exercise logs. Monthly fitness assessments are performed to characterize aerobic capacity and strength levels. Recommendations and adjustments are made to the inflight exercise program as needed, and specific rehabilitation needs may be identified and anticipated.

FIGURE 24-13 Expedition 1 cosmonaut Yuri Gidzenko using the resistive exercise device.

In addition to exercise, other physical and pharmacologic countermeasures are provided and may be used on an individual prescription basis. A decision on the inflight program is made with the crew, FSs, and exercise specialists well in advance of the flight to ensure launch manifesting and availability. Real-time changes may be expected as the program is fine-tuned and assessments are made. A listing of the basic set of countermeasures and assessment methods available to all ISS crewmembers is listed as follows:

A. In-flight (general)
   1. Exercise (including treadmill, cycle ergometer, resistive device; countermeasures and assessment functions)
   2. LBNP (cardiovascular assessment)
   3. Loading suits (Russian "penguin" suit, applies passive continual physical loading)
   4. Thigh cuffs (Russian "brazlet," custom thigh tourniquets worn early in mission to mitigate effects of thoracic fluid shift)
   5. Pharmacologic preparations (motion sickness preparations, sleep medications, metabolic stimulants, nutritional supplements)
   6. Electromyostimulation (Russian device that may be used in combination with LBNP)

B. In-flight (end of mission)
   1. LBNP (progressive cardiovascular challenges in final days before landing)
   2. Fluid/salt loading (volume augmentation on day of landing)
   3. Anti-G garment (pneumatic G-suit on shuttle, elastic "kentaver" garment on Soyuz)
   4. Active cooling (LCG on shuttle)
   5. Recumbent seating for flights greater than 30 days (inherent in Soyuz; specialized system for shuttle)
   6. Pharmacologic preparations (motion sickness, sympathomimetics)

As is evident, this represents a multidisciplinary approach to counteracting those effects of microgravity that become maladaptive for Earth return. A program of medical monitoring and physical assessment is in place to determine the individual's performance as well as the overall efficacy of each method over many individuals. This will better define a baseline approach to protection of crewmembers during prolonged weightlessness.

On-Orbit Medical Assessment

Table 24-9 shows the inflight medical evaluation schedule as ISS operations begin. This serves as a general guideline, and will be adjusted around flight events. Examinations are performed by one of the CMOs, with help as needed from ground personnel. A computer-based program prompts the steps for the physical examination, along with a medical history targeted toward relevant aspects of health in the station environment; observations and data are entered real-time for later downlink to the MCC. Outside of this table, any

TABLE 24-9

Inflight Medical and Fitness Evaluation Requirements for International Space Station

	Interval	*Pre-EVA*	*Post-EVA*	*Prelanding*	*Other*
Body mass measurement	15 d	√	√		
Cardiopulmonary					
ECG					
Lower body negative pressure[a]	60 d			√	Baseline at 2–3 wk
Monitored cycle ergometry (BP, ECG)	60 d				
Aerobic capacity	30 d				
Spirometry/peak flow	30 d				
Laboratory					
Blood	60 d			√	
Urine	30 d	√	√	√	
Hematocrit	60 d			√	Baseline at 7 d
Physical examination	30 d	Brief	Brief	Brief	

Pre-EVA and Post-EVA examinations were performed for EVA occurring after flight Day 21. Prelanding evaluation must be performed within 2 weeks of landing. Blood analyses include sodium, potassium, ionized calcium, glucose, chloride, pH, and hemoglobin.

EVA, extravehicular activity; ECG, electrocardiogram; BP, blood pressure.

[a]Not required by all agencies.

of these tests may be applied as clinically indicated. Medical and fitness data received provides an objective picture of a crewmember's physiologic adaptation and may prompt adjustments to countermeasures, diet, work schedule, and postlanding support. The regularly scheduled conduct of these assessments provides an added benefit of proficiency and familiarity with diagnostic methods and equipment, rendering the CMO more prepared should an acute medical problem arise.

Medical Evacuation and Contingency Crew Return

Throughout the history of space station operations, crews have always had a ready means of return from their platforms; no crew has ever been "dropped off" at a station without another transport attached and ready for evacuation should the need arise. The concept of a means of Earth return from low Earth orbit is an absolute that influences many operational factors. These include crew anthropometry, crew number, onboard medical capability, landing site availability, and ground recovery operations. Three broad scenarios that might lead to an unplanned return are as follows:

1. Interruption of normal launch services due to equipment failures or sociopolitical disturbances
2. An accident on the station rendering the environment uninhabitable, such as a cabin leak or fire
3. Medical contingency involving a problem beyond onboard medical capabilities

Although not always leading to early return, it is worth noting that all of these conditions have occurred during the course of U.S. and Russian spaceflight. From risk analysis based on crew size and work activities, along with examination of medical data from analog scenarios (submarine and surface ships, polar outposts, etc.) and prior spaceflight experience, it is projected that there will be one or two events in the ISS 15-year lifetime prompting a medical return.

Generic attributes of a vehicle supporting contingency crew return from low Earth orbit include the following:

- Ability to accommodate the entire crew in a shirtsleeve environment (time may not allow unstowing and donning of pressure suits)
- Ability to maintain all crewmembers in a recumbent position during entry and landing to minimize body G_z loads
- Highly autonomous landing systems, requiring minimal input from crewmembers who will not be highly proficient on the vehicle
- Ability to separate from the station in a few to several minutes in case of fire, leak, or toxic atmosphere
- Ability to deliver an ill or injured crewmember to a definitive medical care facility on the ground within 24 hours of the decision to evacuate
- Limited stand-alone medical capability, including supplemental oxygen, entry fluid loading for all crewmembers, and accommodation of transport medical hardware

The only manned vehicles currently in use, the U.S. shuttle and the Russian Soyuz, both service the ISS. The shuttle is a multirole transport, ferrying crew and hardware to and from the station and serving as a platform for assembly and maintenance tasks while docked. Entry acceleration forces are relatively gentle, typically 1.2 G over several minutes, with a spike typically near 1.6 G associated with turning to final approach. For flight crewmembers, forces are in the body positive G_z axis. However, a recumbent seat system is used for those returning from flights of 30 days or greater duration, which allows entry and landing forces to be taken in the positive G_x direction. The recumbent seat system is flown only for crew rotation flights, but a crewmember could be returned in the recumbent position on any flight using contingency methods. Although a shirtsleeve cabin, pressure suits are worn for launch and landing; this might be precluded in a complicated medical return. Landing requires a major runway, which inherently simplifies subsequent medical evacuation options, while at the same time implying weather minimums. Primary landing sites include KSC in Florida, Edwards Air Force Base in Southern California, and White Sands, New Mexico. If possible, an urgent return would await a landing opportunity at one of these sites, of which there are several per day. The shuttle has limited loiter time on the ISS, usually 5 to 10 days. As such, the shuttle will nominally be docked to the ISS and available for contingency transports a relatively small fraction of time. Vehicle processing and preparation requirements essentially preclude the option of launching an unplanned shuttle to evacuate the ISS crew on a timely basis. For a chronic or subacute medical problem, a crewmember might be exchanged on a scheduled flight of opportunity to preclude the chance of the problem worsening on orbit.

The Russian Soyuz is a dedicated three-person CTV, and in its current iteration (Soyuz TM) is certified to remain on orbit for 180 days. The vehicle lands in the Kazakh steppe east of the Baikonur launch site, using a parachute and soft landing engines in a highly automated return sequence. Entry acceleration forces are taken in the positive G_x axis for the recumbent crew and peak at about 4 G. Landing impact involves a 4-G pulse of 0.4 seconds, again in the positive G_x axis. As for the shuttle, pressure suits are worn for launch and entry, but this requirement might be waived for a crewmember requiring medical evacuation. Recovery forces are deployed to the landing site through helicopter and include several medical specialists. Stabilization at the landing site of an ill or injured crewmember would be followed by helicopter transport to the nearest large runway, followed by aircraft transport to a tertiary care facility. Unlike the shuttle, the Soyuz is not significantly constrained by weather at the landing site, improving the chances of recovery by experienced teams in the event of contingency returns. For the near future, this three-person transport dictates the number of long-term ISS crewmembers. The Soyuz, with its small volume and tightly constrained entry couch fit requirements, is the limiting constraint on ISS crewmember height and weight. A proven and reliable vehicle, the Soyuz adequately fulfills the role of returning the crew under circumstances of interrupted launch services or all-crew evacuation. However, the tight quarters and landing impact make it a less than optimal vehicle for return of an ill or injured crewmember.

To increase the crew size to six, emergency return alternatives must be developed, including multiple Soyuz vehicles or production of a single new spacecraft with long-term loiter potential and the ability to accommodate the full crew complement. The ISS program has over the years shifted away from the concept of a dedicated onsite rescue spacecraft in favor of incorporating this capability into standard duty vehicles. A next generation vehicle (currently called the crew exploration vehicle, or CEV) is under development which would serve the purpose of delivering up to six crewmembers to the ISS, remaining on station for standard crew rotations of six months. Like the Soyuz, this vehicle would allow rapid separation and earth return within a few hours.

For all vehicles, a system of contingency and emergency landing sites must be available, with a set of target sites identified and selectable real-time based on the character of the orbit at the time of evacuation. These target sites are already in place for the Soyuz and shuttle, with trained recovery teams available and an organized plan to use local medical resources. In addition, the ground recovery operation must include immediate on site triage and medical care with a means of stabilization for transport. Ground medical personnel must be familiar with the vehicle and its inherent hazards and have an understanding of the basic physiologic effects of long-duration microgravity exposure. Whatever problem might prompt a medical return will be superimposed on the overall state of deconditioning described earlier in this chapter. Although the launch and landing phases for any spacecraft represent the greatest mission hazard, the medical support infrastructure is well established at the Soyuz and shuttle launch and prime landing sites. Although ground teams stand ready to support a landing, the unplanned return of one of these spacecraft and rapid unexpected remote deployment of the landing team presents hazards for ground personnel. These risks must be included when considering emergency deorbit and medical evacuation.

Extravehicular Activity Operations

EVA will always remain one of the more hazardous activities of spaceflight. Although astronauts performed EVAs during the Gemini, Apollo, and Skylab programs, NASA achievements in EVA have been primarily associated with short-duration shuttle flights. Over the last two decades, most of the Russian EVA experience has been associated with long-duration flight, performing Salyut and Mir station assembly and maintenance tasks. In either case, typical EVA sorties are physically and mentally exhausting, although the challenges and satisfaction involved make EVA a highly desired activity for crewmembers. The ISS will draw upon both experience bases, utilizing shuttle-based EVAs for complicated assembly tasks associated with new elements, and station-based EVAs more oriented toward maintenance and repair. Two separate EVA suits, support systems, and control centers make EVA one of the more complexoperations associated with the ISS. Compared with short-duration spaceflight, EVA associated with long-duration flight involves the following significant differences:

- Crewmembers are physically deconditioned due to microgravity; an EVA may occur several months after launch.
- Ground examination and medical certification may precede the EVA by several months.
- EVA task training in high-fidelity ground facilities, such as water immersion, is more remote; applies to crewmember and ground personnel.

- EVA suit checkout and qualification by ground personnel is more remote.

These differences are approached in the practical sense by maintaining physical conditioning through exercise countermeasures oriented specifically toward EVA and employing crewmembers to perform suit, system, and medical checkout activities. Real time ground support is extensive during these onboard activities, and preparation time is understandably increased as compared with short-duration shuttle flight EVA. The United States and Russia have each developed EVA systems, and both of these are accommodated in a nearly unchanged form on the ISS. The operational authority during an EVA, medical and otherwise, rests unconditionally with the group controlling the suit, regardless of the nationality of the occupant. Each suit type egresses the station from its own airlock and support facility, and the systems are decidedly different in form and control. Two individuals always perform EVA, and it has been determined for ISS that these will always be using the same suit type to simplify ground support and avoid confusion.

The U.S. EMU is pressurized to 4.3 psia, classically requiring a 4-hour oxygen prebreathe before decompressing from cabin pressure (sea-level equivalent) to working suit pressure for mitigation of risk of DCS. Alternatively, if the crewmember is held at the intermediate pressure of 10.2 psia for 12 hours as a staged decompression step, final decompression to suit pressure requires a 40-minute prebreathe. (This intermediate decompression stage has been routinely used on the shuttle, and may be used on the ISS by isolating the EVA crewmembers in the airlock on the day before scheduled EVA and selectively decompressing this module to 10.2 psi.) More recently, protocols of oxygen prebreathe have been utilized in combination with aerobic exercise to enhance tissue perfusion and accelerate the nitrogen washout. The EMU is highly modular, requiring more than 130 measurements to ensure optimal fit, and is donned at the waist with assistance; self-donning is possible but difficult. The EMU is certified for 25 EVA sorties of up to 7 to 8 hours before being returned for ground refurbishment and recertification. The lead FS and biomedical engineers assigned to the mission from MCC-Houston perform medical monitoring of EMU sorties. Ground communication between the MCC-Houston capcom (capsule communicator) and EVA crew is monitored, and the FS would speak directly with the crew only in an emergency situation.

The Russian Orlan EVA suit is pressurized to 5.7 psi, sacrificing a degree of manual dexterity for a lowered risk of DCS in a long recognized EVA tradeoff. Typical prebreathe before decompressing from sea level is 40 minutes, usually done in the suit during system and airlock preparation. The Orlan is produced in a single size, with various lengths adjusted with dials and cables. With its large rear-entry access, the Orlan is easily and quickly donned by an unaided crewmember. The Orlan is certified for 10 EVA sorties or 4 years of on-orbit lifetime, and in the Mir program has been typically loaded into a Progress freighter for disposal during atmospheric destruction. The group responsible for medical monitoring of the Orlan is a multidisciplinary team representing the Institute for Biomedical Problems, the Gagarin Cosmonaut Training Center, Rocket Space Corporation Energia, and Svezda, designers and builders of the Orlan. Systems and medical specialists routinely speak directly with the EVA crewmembers to provide technical guidance and assess well-being.

In the medical preparation for EVA during ISS missions, several points of evaluation are performed. A review of countermeasure performance and general level of physical conditioning is conducted from routine exercise data. This is augmented by formalized cycle ergometry evaluations using both legs and arms performed within 10 days of scheduled EVA, along with handgrip dynamometry. For a sortie occurring after 21 days inflight, a medical examination is conducted by a CMO. Blood draws for medical operations or investigations, which might involve finger lancets or venipuncture, are prohibited within 7 days of EVA. The FS or Moscow medical group obtains examination results and endorses readiness to the flight director. A final evaluation is performed on the day before EVA targeted toward the upper airways, ensuring nasopharyngeal patency before the pressure excursion. The FS and EVA crewmembers discuss readiness and recommendations during a PMC. For a particularly demanding EVA, body mass may be measured immediately before and after suit donning and doffing to assess fluid loss.

During the actual EVA operation for either suit, ground medical personnel monitor electrogastrogram EGG along with ECG-derived heart rate, suit environmental data, metabolic rates derived from these parameters, and air-to-ground communications. Russian medical team leads may directly query the crew regarding physical symptoms and tolerance. The Orlan adds respiratory rate to the monitored parameters. Good biomedical telemetry is verified by medical operations during suit donning. During periods of satellite blockage, biomedical data are recorded for later downlink when communications are reestablished. In addition, radiation specialists closely monitor solar activity and excursions through the South Atlantic Anomaly. Each crewmember also wears a passive personal dosimeter during the EVA, which is later returned for ground analysis. Along with monitoring, the medical teams are ready to assist with problems or mishaps that might arise, particularly DCS, barotrauma during repressurization, musculoskeletal strains, and physical overwork.

Following the EVA, medical examination may be performed by the CMO as clinically indicated. Typical findings include minor trauma to the nail beds from EVA gloves, skin abrasion points on the hands, wrists, and hips from suit chafing, soreness in the hands, wrists, and shoulders, and generalized fatigue. Again, private medical communication is afforded between crewmembers and FSs to offer treatment recommendations as indicated and discuss other relevant factors, such as workload or sleep schedule changes. Scheduled EVAs on successive days are prohibited, and adequate rest and time off is mandatory. Should DCS arise that is refractory to recompressing to cabin pressure, 100% oxygen at ambient cabin pressure would be administered. It is possible to remain in the suit and add its pressure to station pressure, but definitive hyperbaric treatment is not available on the ISS. A complicated unresolved case might prompt a return to Earth.

Postflight Rehabilitation Programs

Postflight rehabilitation begins immediately after landing as the crew egresses their returning spacecraft, whether the shuttle or Soyuz. Mission-assigned medical personnel are on hand to provide care and perform medical assessment in the immediate postlanding period. Typically, crewmembers are exhausted and weak, with several physiologic systems beginning the readaptation process. Despite similar exercise countermeasures performance, there is a high degree of individual variability regarding physical capabilities during the immediate period. For all crewmembers, physical demands should be minimized as they are passively reintroduced to gravity. Medical and support personnel must assure stability for transport by aircraft from the landing site to an initial crew rehabilitation facility, either at JSC in Houston or the Gagarin Cosmonaut Training Center in Star City.

Three main elements of rehabilitation following long-duration spaceflight are passive and gentle progressive physical loading challenges, reintroduction to familiar surroundings and home life, and abundant rest. Although time is made available for postflight investigations, technical debriefs, and public appearances, medical care and rehabilitation take priority over all other activities. A rehabilitation team includes as a minimum mission-assigned FSs, exercise specialists, nursing and other clinical specialists, and psychological support personnel. Daily team meetings for the first several days ensure a multidisciplinary approach, and that rehabilitation efforts are balanced with other postmission activities. Crew work and rest guidelines are strictly enforced. A typical program of physical assessment is reflected in Table 24-8; as much as possible, blood draws and other assessment means are coordinated with medical investigations to minimize sample collections and clinic time. Significant milestones include returning to the home environment, driving, flying aircraft and other training activities, and eventual return to full spaceflight status and eligibility for another long-duration mission. Physiologic markers include aerobic capacity, strength of postural muscles, functional neurologic capacity, RBC mass, and bone density. In all of these, return to the preflight levels is the overriding goal. Also, radiation exposure is quantified and applied to annual and career limits.

A general plan for rehabilitation has been developed jointly by IP participants, augmented by specific individual rehabilitation programs for each crewmember. These also include plans for postflight travel. ISS missions imply that some fraction of the crew will land in a nonnative country, and timely return to the familiar home environment is desirable as early as possible. This necessitates international travel, which is best deferred for 2 or more weeks of initial postlanding rehabilitation efforts. If possible, family members should be available at the rehabilitation site. Reintroduction to premission work activity should be gradual and only following the greater percentage of physical and social rehabilitation. The Russian practice is to provide returned cosmonauts with a sanitorium experience, accompanied by family members, FS, and rehabilitation specialists once initial medical evaluations and technical debriefs are completed. Bearing in mind the entire mission experience, including the intensive training period, inflight activity, and acute period of readaptation, such a time-off period is highly desired.

EXPLORATION CLASS MISSION MEDICAL CARE

The provision of medical care for exploration-class missions to Mars and the Moon will present unique challenges for mission planners, FSs, and crewmembers. A major difference from current mission parameters is the lack of rapid return to medical facilities on Earth, distance and communications limitations that preclude telepresence techniques and require more crew autonomy, and microgravity during transit plus reduced gravity on the surface. The gravity on the Moon is approximately one sixth that of Earth and on Mars approximately 38% of the Earth's gravity. In addition, the relative isolation, crew cultural differences, and lack of radiation protection from the earth's geomagnetic fields increases the need for psychological support and radiation protection. Clearly, the medical systems for exploration-class missions will need to be more extensive than that found on current missions to low earth orbit; however, it will be impossible to provide medical care for all conceivable medical problems. A certain amount of risk will have to be accepted by the crew and mission planners.

Planning medical care for long-duration missions begins with medical risk assessment from the longitudinal data from the astronaut population, assessment of the effects of the reduced or microgravity environment, evaluation of operational parameters for the transfer vehicles and surface habitat, and consideration of available medical diagnostic and treatment technology (22). It is hoped that data from multiple prolonged missions to the ISS and some experience on the Moon can improve the understanding of medical risk for astronauts who depart for Mars. In addition, the ISS and Moon exploration offer the opportunity to develop hardware and procedures for both the microgravity and reduced-gravity environments before committing to more remote missions. Other analog environments may also be used for assessing risk and intervention, but as more experience is generated from actual spaceflights, the less valuable become the data from terrestrial analog environments.

From a medical perspective, prevention of medical problems through selection constraints, preventive medicine programs, preflight assessment, and selective prophylactic intervention will be of paramount importance. It is likely that crewmembers for remote long-duration spaceflight would have elective endoscopic removal of their appendix before flight. It is hoped that biochemical protection can be developed to augment spacecraft shielding to reduce the impact of galactic cosmic radiation or solar particle events. Great effort will be made to convert potentially surgical conditions to medical conditions. However, there is no doubt that limited surgical capability will eventually be required, either through an episodic illness or trauma. Microgravity surgical treatment capability, including endoscopy, has been developed during zero-G flights on the jet aircraft and during shuttle flights (23–25). Although there have been no large impediments to surgical procedures, the experience to date has been primarily limited to animals that are sacrificed. Further development of anesthetic procedures, equipment, and procedures for humans will be required. The ability to train and practice novel procedures on the actual crewmember's pathology using virtual reality fly-through technology with haptic feedback and appropriate input from earth-based consultants may enable crewmembers to successfully provide treatment that could be outside their medical experience base (26). Laparoscopic simulated surgery has already been successfully tested during zero-g flights.

Crewmembers for exploration-class missions will require multiple skills, and a physician crewmember will need to have considerable expertise in areas outside of medicine. In fact, it is likely that medical skills will be of secondary importance for that individual. Although there has been considerable discussion regarding the ideal physician for long-duration missions, many physicians suggest a physician crewmember who shares their own skill. However, the most important medical skill for this type of mission may be the ability to integrate medical informatics and learn novel techniques and solutions to problems not encountered in previous medical training. In addition, the ability to provide psychological support and improve the problem-solving and coping skills of the team may be equally important to surgical and technical skills.

Owing to mission duration, there will also be some erosion of earth-based skills. Onboard training scenarios and realistic practice will be required to keep skills sharp. Maintaining technical skills will be important because all procedures must be done autonomously, yet medical decision making can generally be augmented from earth. Mars varies from 35 to 210 million mi from earth and communication can take from 7 to 40 minutes roundtrip. Because the communication is line-of-site, there will be times when no communication at all is possible.

It is inevitable that humans will eventually go beyond low earth orbit and explore our nearby planets, moons, or asteroids. Those who plan the missions and the medical care for the crews will have to reach 10 to 20 years into the future for the hardware, techniques, and procedures for those missions (27). A partnership between the space program, universities, and commercial providers will be required to accomplish this task. Some of the breakthroughs during this process will eventually be used for clinical care on earth, but some developments will never reach clinical usefulness. However, the potential scientific returns from exploration-class missions and the far-reaching medical technology that results from developing crewmember health care systems may be revolutionary for those inhabiting planet earth.

REFERENCES

1. National Aeronautics and Space Administration (NASA). *Biomedical results from Skylab*. NASA SP-377. Washington, DC: NASA, 1977.
2. Sawin CF, Taylor GR, Smith WL, eds. *Extended duration orbiter medical project. Final report 1989–1995.* NASA/SP-534. Johnson Space Center, Houston: National Aeronautics and Space Administration, 1999.
3. Elliott AR, Prisk GK, Guy HJB, et al. Forced expiration and maximum expiratory flow-volume curves during sustained microgravity on SLS-1. *J Appl Physiol* 1996;81:33–43.
4. Fritch-Yelle JM, Charles JB, Crockett MJ, et al. Microgravity decreases heart rate and arterial pressure in humans. *J Appl Physiol* 1996;80:910–914.
5. Buckey JC Jr, Gaffney FA, Lane LD, et al. Central venous pressure in space. *J Appl Physiol* 1996;81:19–25.
6. Shykoff BE, Farhi LE, Olszowka AJ, et al. Cardiovascular response to submaximal exercise in sustained microgravity. *J Appl Physiol* 1996;81:26–32.
7. Davis JR, Jennings RT, Beck BG, et al. Treatment efficacy of intramuscular promethazine for space motion sickness. *Aviat Space Environ Med* 1993;64:230–233.
8. Jennings RT. Managing space motion sickness. *J Vestib Res* 1998;8:67–70.
9. Paloski WH, Reschke MF, Black FO, et al. Recovery of postural equilibrium control following spaceflight. *Ann N Y Acad Sci* 1992;656:747–754.
10. Highstein SM, Cohen B. Neurolab mission commentary. *Curr Opin Neurobiol* 1999;9:495–499.
11. Alfrey CP, Udden MM, Leach-Huntoon C, et al. Control of red blood cell mass in spaceflight. *J Appl Physiol* 1996;81:98–104.
12. Stein TP, Leskiw MJ, Schluter MD. Diet and nitrogen metabolism during spaceflight on the shuttle. *J Appl Physiol* 1996;81:82–97.
13. National Aeronautics and Space Administration (NASA). *Astronaut medical standards, selection and annual medical certification*. Revision A. (JSC)-24834. Johnson Space Center, Houston: NASA, 1999.
14. National Aeronautics and Space Administration (NASA). *Astronaut medical selection manual*. (JSC)-23086. Johnson Space Center, Houston: NASA, June 1999.
15. Hamm PB, Nicogossian AE, Pool SL, et al. Design and current status of the longitudinal study of astronaut health. *Aviat Space Environ Med* 2000;71:564–570.
16. Putcha L, Berens KL, Marshburn TH, et al. Pharmaceutical use by US astronauts on space shuttle missions. *Aviat Space Environ Med* 1999;70:705–708.
17. National Aeronautics and Space Administration. *International Space Station medical operations requirements document*. Revision A. (JSC)-50260. Johnson Space Center, Houston: NASA, 1998.
18. National Aeronautics and Space Administration. *International Space Station joint medical operations implementation document*. Revision A. (JSC)-50480. Johnson Space Center, Houston: NASA, May 2000.

19. Nicogossian AE, Robbins DE. Characteristics of the space environment. In: Nicogossian AE, Huntoon C, Pool SL, eds. *Space physiology and medicine*, 3rd ed. Philadelphia: Lea & Febiger, 1994.
20. Cucinotta FA, Schimmerling W, Wilson JW, et al. *Space radiation cancer risk projections for exploration missions: uncertainty reduction and mitigation*. (JSC)-29295. Johnson Space Center, Houston: National Aeronautics and Space Administration, January 2001.
21. National Council on Radiation Protection and Measurement (NCRP). *Recommendations of dose limits for low-earth orbit*. *NCRP Report 132*. Bethesda: NCRP, 2000.
22. Billica RD, Simmons SC, Mathes KL, et al. Perception of medical risk of spaceflight. *Aviat Space Environ Med* 1996;67:467–473.
23. Campbell MR, Billica RD, Jennings RT, et al. Laparoscopic surgery in weightlessness. *Surg Endosc* 1996;10:111–117.
24. Kirkpatrick AW, Campbell MR, Novinkov OL, et al. Blunt trauma and operative care in microgravity: a review of microgravity physiology and surgical investigations with implications for critical care and operative treatment in space. *J Am Coll Surg* 1997;184:441–453.
25. McCuaig K. Surgical problems in space: an overview. *J Clin Pharmacol* 1994;34:513–517.
26. Lange T, Indelicato DJ, Rosen JM. Virtual reality in surgical training. *Surg Oncol Clin N Am* 2000;9:61–79.
27. Satava RM, Jones SB. Preparing surgeons for the 21st century: implications for advanced technology. *Surg Clin North Am* 2000;80:1353–1365.

RECOMMENDED READINGS

Barratt MR, Pool SL, eds. *Principles of clinical medicine for spaceflight*. New York: Springer-Verlag, 2002 (in press).

Johnson RS, Dietlin LF, eds. *Biomedical results from Skylab*. NASA SP-377. Johnson Space Center, Houston: National Aeronautics and Space Administration, 1977.

Nicogossian AE, Huntoon CL, Pool SL, eds. *Space physiology and medicine*, 3rd ed. Philadelphia: Lea & Febiger, 1994.

Sawin CF, Taylor GR, Smith WL, eds. *Extended duration orbiter medical project. Final report 1989–1995*. NASA/SP-534. Johnson Space Center, Houston: National Aeronautics and Space Administration, 1999.

CHAPTER 25

Aircraft Accidents: Investigation and Prevention

Stephen J. H. Véronneau and Eduard M. Ricaurte

> Mishaps are like knives, that either serve us or cut us, as we grasp them by the blade or the handle.
>
> —*James Russell Lowell*

> We shall draw from the heart of suffering itself the means of inspiration and survival.
>
> —*Winston Churchill*

There has been a massive increase in the online community with a commensurate increase in the ability of Internet-based searches to find and retrieve safety information. Aviation safety databases maintained by individuals and government agencies have increased in scope and content. A public aeromedical mailing list, published by an Internet list server instantly from reader postings, has existed for more than a decade and knits together aeromedical practitioners the world over. The safety statistics and research findings presented here are available from various government, industry, academic, and aviation advocate organizations through their various websites, so the reader will be able to acquire the most up-to-date information to complement the information presented in this chapter. The National Transportation Safety Board (NTSB) investigation and studies, the Air Accidents Investigation Branch, the General Aviation Manufacturers Association data, the Flight Safety Foundation, the National Business Aircraft Association, the Aircraft Owners and Pilots Association (AOPA) safety database, the Federal Aviation Administration (FAA) Aviation Safety Data, and the Civil Aerospace Medical Institute (CAMI) publications are all available online. These websites and more are easily retrieved by entering in the search terms "aviation safety" or the title of the organization in a search engine. Many governments have committed to making much of its safety data available online to provide a comprehensive, convenient, and low-cost access to nonprivacy materials. The development of powerful, comprehensive, and logical Internet search engines will allow the reader to continue to find such safety data even as the Internet addresses of the various entities may change over time. Some useful universal resource locators (URLs) will be included in the text and some are appended at the end of this chapter to find these various information resources. In addition, the number of agencies that have become involved with the aircraft accident disaster scene has increased, resulting in increased complexity in managing an aircraft accident investigation. Although the safety statistics may change over time to reflect an improvement in aerospace safety, and technology continues to add more sophisticated accident reconstruction tools, many of the original investigative techniques for medical aircraft accident investigation are sound and will serve the aerospace medicine practitioner well in their participation in aircraft accident investigations.

PURPOSE OF THE INVESTIGATION

There are many reasons to investigate aerospace accidents and incidents. Primarily there is the need to prevent future occurrences. Of secondary importance is the need to learn about the failure modes of people, equipment, and systems in aerospace. A sudden occurrence of a mass disaster, such as an aircraft accident, with the attendant instant media coverage around the world, arouses public concern. After the accident, affected individuals and organizations will have substantial personal interests in the findings and determinations of accident investigations. Survivors of those who die in the crash are interested in obtaining adequate explanation as they try to come to terms with the loss of loved ones. The local government has an interest in ensuring the health, safety, and welfare of the public. It wants to be sure that no crime against the state or individuals has been committed and that there is no risk of infectious disease. The local jurisdiction is responsible for determining the manner of death of the accident victims and to properly handle the human remains. Environmental damage and hazardous materials caused by the accident bring other federal agencies into the investigation and cleanup efforts. The federal government has many of the same interests as the local government. In addition, it is also concerned with the safe and efficient operation of interstate commerce. There will always be substantial legal proceedings occurring in background of investigations and this should not deter the medical accident investigator from their tasks. The recent development of commercial space flight will further necessitate the development of resources to properly investigate space-based accidents.

Investigators feel the pressure of all these interests, but they must not forget that the primary purpose of aircraft accident investigation is to prevent future accidents, injuries, and fatalities. To achieve this goal, they must thoroughly investigate all injuries and circumstances of a mishap, avoiding the placing of blame and seeking the root causes of the accident. They must concentrate on the most proximal of events in the complex sequence of linked events that always precede the accident occurrence, and must look for all factors that may have contributed to the accident. They must also avoid premature analyses and conclusions by keeping an open mind and concentrating on collecting facts during the investigation.

ROLE OF THE PHYSICIAN IN AIRCRAFT ACCIDENT PREVENTION

This chapter provides useful information for all who participate in accident investigation and prevention activities. There are many types of individuals from many disciplines that comprise the modern group-based investigation of the medical aspects of accidents. In this group, one will find anthropologists, pilots, flight attendants, air traffic specialists, psychologists, physiologists, coroners and medical examiners, safety engineers, and aerospace medicine practitioners. The primary role of the aerospace medicine practitioner in aerospace accident investigation is to examine both the causes and consequences of the accident, in order to learn how to prevent the occurrence. A secondary role is to document from the consequences of the accident how to improve survivability and to reduce deaths and injuries that occur when the accident is not prevented.

There are additional means by which military flight surgeons, aviation medical officers, and designated aviation medical examiners (DAME) participate in preventing aircraft accidents. As medical practitioners, they have a role in certifying their pilot patients fit for flight. Some practitioners develop comprehensive preventive medicine programs for their pilots. In most countries, a physician is making a finding, under the regulations of those countries, that the pilot is not likely to sustain an incapacitation during the period of the validity of the certification, which may span time intervals of several months to several years. In the case of multicrew cockpit operations the certification that a particular pilot is fit, in other words that the pilot will not have an in-flight incapacitation, is important. In single-pilot cockpit operations, it is potentially a life-or-death decision because the certified pilot may be the only person able to fly the aircraft. Therefore if they are incapacitated there is almost a certainty of a crash.

There is a potential conflict in treating pilots and always maintaining their confidentiality. In some cases, aviation safety problems are prevented when treating physicians (or other health care professionals) after providing medical care, also forward information regarding the pilot's medical condition to aviation authorities. Some jurisdictions, like Canada, require the reporting to the federal civil aviation authorities of serious medical conditions in pilots that may pose aviation safety risks, and require that aircrew members identify themselves as aircrew to health care providers. DAMEs can serve as the pilot's best advocate to maintain medical certification of fitness to fly. However, accidents have occurred when pilots hid known medical conditions, and when some physicians participate in the misdirected actions of protecting or assisting the pilot in concealing medical conditions. A fatal accident occurred when a pilot became incapacitated and the investigation uncovered the deceit of the airmen and his aviation medical examiner (AME) in concealing cardiac disease (NTSB Case Number: CHI02FA172). Investigation of medically related accidents and incidents can also serve as a quality control function for medical certification authorities by providing long-term data to assist in evidence-driven medical certification decision making.

DEFINITIONS OF INCIDENT, ACCIDENT, AND FATALITY

The NTSB defines *accident* as "an occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which any person suffers death or serious injury as a result of being in or upon the aircraft or by direct contact with the aircraft or anything attached thereto, or the aircraft receives substantial damage. *Fatal injury* means any injury which results in death within 30 days of the accident. *Incident* means an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations" (1).

It is important to understand the background of cultural and historical perceptions of accidents. In the history of crash investigation, famous researchers showed that aviation accidents were not inevitable acts of nature or unpreventable occurrences. Highlighting this cultural misperception, dictionary definitions of accident have many clauses and interpretations. One of the most comprehensive definitions of accident can be found in the 1999 edition of the Microsoft (MS) *Encarta World English Dictionary*, partly excerpted here, *accident** is defined as follows (2):

> 1) **Chance**: the way things happen without any planning, apparent cause, or deliberate intent; 2) **Crash**: a collision or similar incident involving a moving vehicle, often resulting in injury or death; 3) **Mishap**: an unplanned and unfortunate event that results in damage, injury, or upset of some kind; and 4) **Chance happening**: an event that happens completely by chance, with no planning or deliberate intent.

None of these definitions convey the proper sense that accidents can be prevented. The legal NTSB definition will be given later. Although *accident* is a commonly accepted term, many of the aerospace occurrences that are called *accidents* are not unforeseen, and some, to the aviation safety expert, are predictable in that they have readily apparent causes. The occurrences of deliberate destructive acts, such as suicide or sabotage, are not included in safety data rates by the NTSB, the FAA, or the industry. Accidents resulting from suicide and sabotage are not addressed in this chapter, although there have been useful studies of the use of aircraft as instruments of self-destruction. U.S. military forces use the term *mishap* rather than accident. Some researchers advocate the term *crash*, but not all accidents or incidents involve a crash event. Since 1995, coordinated by the Joint Committee on Aviation Policy, accidents involving public use aircraft have been investigated by the affected government agency, using NTSB standards or staff participation, and have been reported to the NTSB. They are not discussed here.

SAFETY STATISTICS

With the United States incurring much of the world's aviation activity, and carrying slightly less than half the world's airline passengers, there is a wealth of data in the National Airspace System (NAS). The FAA is responsible for monitoring and managing the NAS and all safety measures and is establishing an Aviation Safety Information Analysis and Sharing System (http://www.faa.gov/safety/). Online data searches can be made of aviation incidents from the FAA investigations, and aviation accidents, from NTSB investigations. The NTSB also makes its investigation records available to online query and the datasets can be downloaded in their entirety (www.ntsb.gov).

The NAS Information Monitoring System [National Airspace System Information Monitoring System (NAIMS)] produces the *Aviation Safety Statistical Handbook* (3). As of April 2007, this handbook contains 5 years of data, with accident rates for large air carriers, commuter air carriers, air taxis, general aviation, rotorcraft, and midair collisions. Five years of incident rates for air carriers, commuter air carriers, air taxis, general aviation, and rotorcraft are also provided. The NAIMS segments monitored comprise "Near Midair Collisions," "Operational Errors," "Operational Deviations," "Pilot Deviations," "Vehicle/Pedestrian Deviations," "Surface Incidents," "Runway Incursions," "Flight Assists," and NTSB accident data. In addition to the safety data and charts, contact information, an acronym/abbreviation list, and a glossary are provided. There are numerous other data products, such as the Administrators Fact Book and links to other safety datasets, such as the Bureau of Transportation Statistics, that can be found at the website listed previously.

The FAA Office of System Safety originally sponsored a worldwide project called *Global Aviation Information Network* (GAIN), whose purpose is to develop a variety of safety measures that can be collected and shared worldwide. This sponsorship ended in 2007. The Flight Safety Foundation now maintains many of the products that were developed in GAIN. The Boeing aircraft industry company tracks safety data worldwide for large jet aircraft, regardless of manufacturer, and produces an annual summary that can be downloaded in portable document format from their website (*Statistical Summary of Commercial Jet Airplane Accidents: Worldwide Operations* 1959–2005, published May 2006). The number of jet aircraft worldwide has steadily increased to 20,037, and the number of commercial departures and flight hours has grown to 40.0 million and 19.2 million, respectively (Figure 25-1). These data clearly show a remarkable decrease in the worldwide accident rate, but this rate has leveled off and has remained relatively stable over the last two decades (Figure 25-2). Worldwide summary data of accidents by damage and injury is illustrated in Figure 25-3. An NTSB study of airline safety revealed that passenger enplanements in the United States more than doubled in the 16 years following 1983 (4). According to FAA data, there were 741 million domestic passenger enplanements in the United States in 1996 (not including international passenger traffic) and 2.2 billion worldwide according to International Civil Aviation Organization (ICAO) data. According to recent FAA forecasts, this growth is expected to continue, approaching 1 billion enplanements by 2015. Despite the growing demands on the U.S. aviation system, the system continues to maintain its high level of safety. The accident rate for commercial aircraft has remained approximately the same for the last two decades. If the accident rate continues, however, increased traffic projected over the next 10 years will be accompanied by a commensurate increase in the number of aircraft accidents. To prevent this from

*Fourteenth century, via French, from Latin *accident*, the present participle stem of *accidere* "to happen," literally "to fall to," from *cadere* "to fall, die" (source of English *cadaver* and *chance*). From the *Encarta World English Dictionary*, Microsoft corporation, 1999.

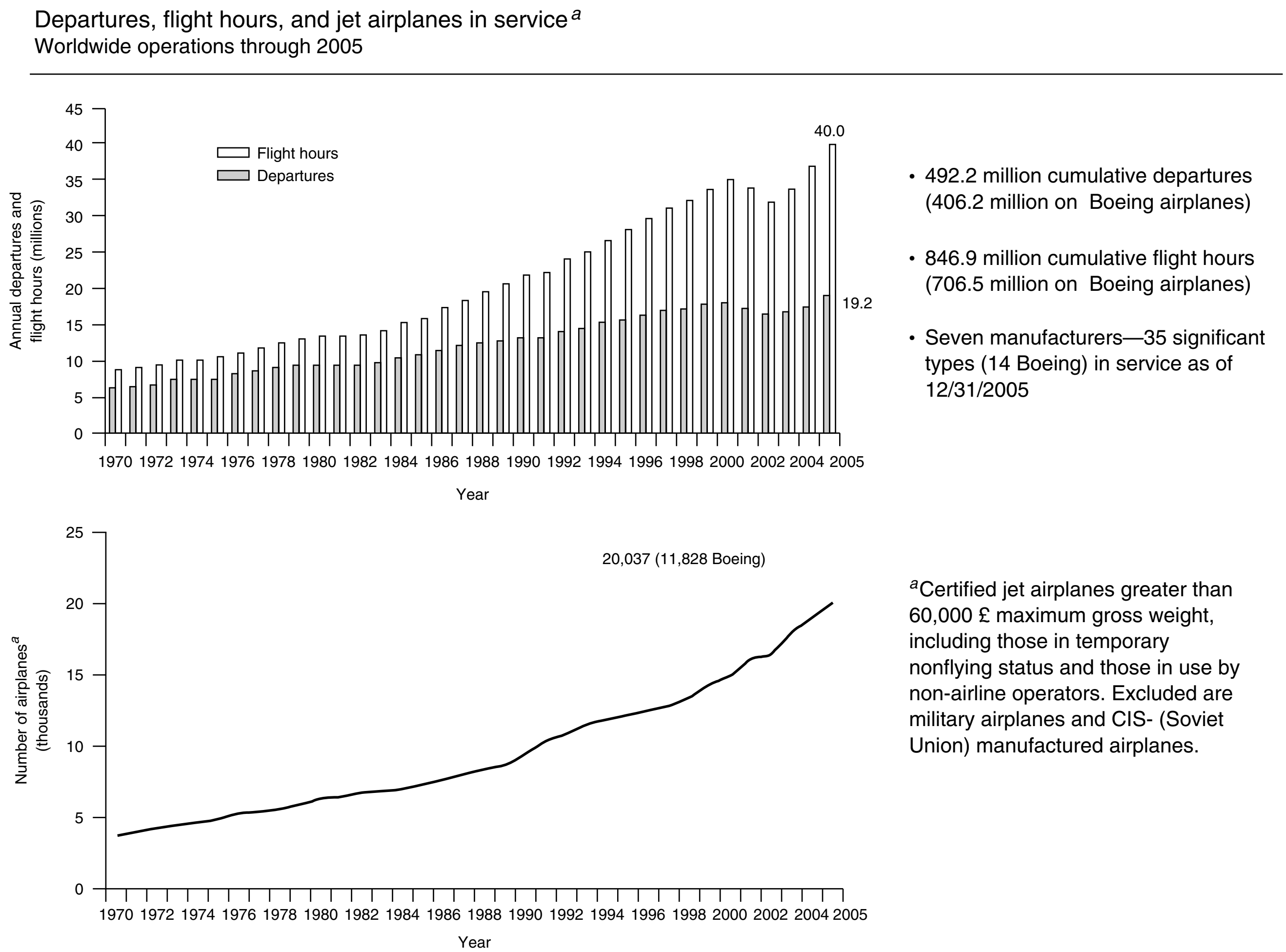


FIGURE 25-1 Worldwide jet operations from 1970 through 2005 illustrating the number of aircraft accidents, deaths, and death rate per 100 million passenger miles (Boeing safety data, May 2006).

occurring, government agencies are working with industry to reduce the accident rate and number of fatalities. There are two ways to prevent fatalities in air travel: by preventing accidents and by protecting aircraft occupants in the accidents that do occur. A reduction in accident rates provides an indication of the success of accident prevention; examining occupant survivability can indicate the positive results from occupant protection. Examining occupant survivability in aviation accidents can help dispel a public perception that most air carrier accidents are not survivable, and can identify factors that can be acted upon to increase survivability in the accidents that do occur. The aerospace medicine practitioner has an important role in a multidisciplinary effort to examine both aeromedical and human factor inputs into accident causation. Aerospace medicine practitioners are ideal assets in determining the consequences of the accidents by learning how to practice primary prevention of the occurrence and documenting data from the consequences of the accident to learn how to improve secondary prevention of the deaths and injuries that result post impact. There is also much to be learned from studying the survival factors in the postimpact environment, such as factors that affect the crews' ability to conduct the emergency egress, and the passengers' success or failure in evacuating the aircraft.

Safety Perspective

To understand how low aviation fatalities are related to the overall transportation safety record, and with accidents in general, it is appropriate to point out that passenger transportation accidents of all modes account for approximately one fourth of all accidental deaths. Of all types of transportation, only transit buses have a lower death rate than scheduled airliners (Table 25-1).

Later in this chapter the various types of aviation operations will be compared. A perspective of various types of risk can be made using data from the Department of Transportation (DOT) Office of Hazardous Materials Safety. This office publishes a *Risk Comparison,* which contains a variety of activities, including natural phenomenon, and the risk of accidental death in the United States for the period 1999 to 2003 (Table 25-2) (http://hazmat.dot.gov/riskmgmt/riskcompare.htm).

For Part 121 and 135 air carriers, with a 5-year average of 138 deaths, they calculate a general population risk of death

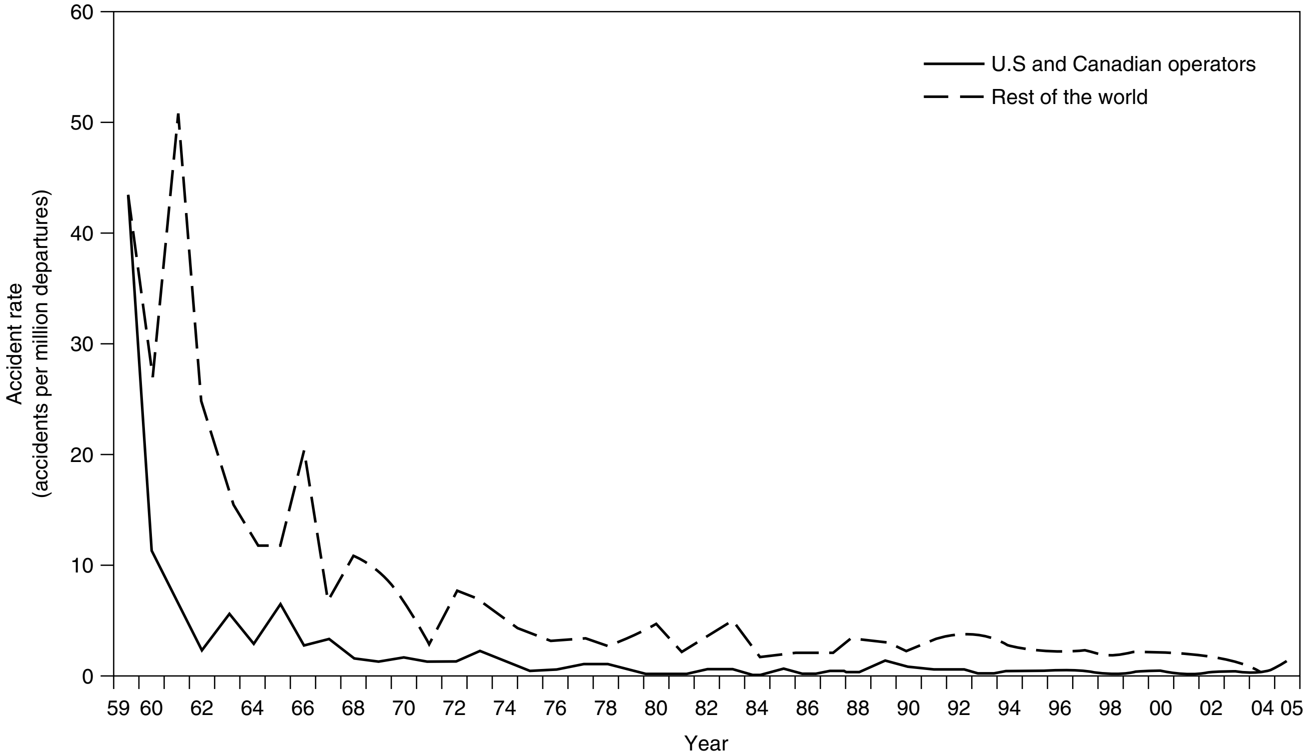


FIGURE 25-2 Worldwide jet accident rates 1959 to 2005 for U.S. and Canadian operators compared with the rest of the world (Boeing safety data, May 2006).

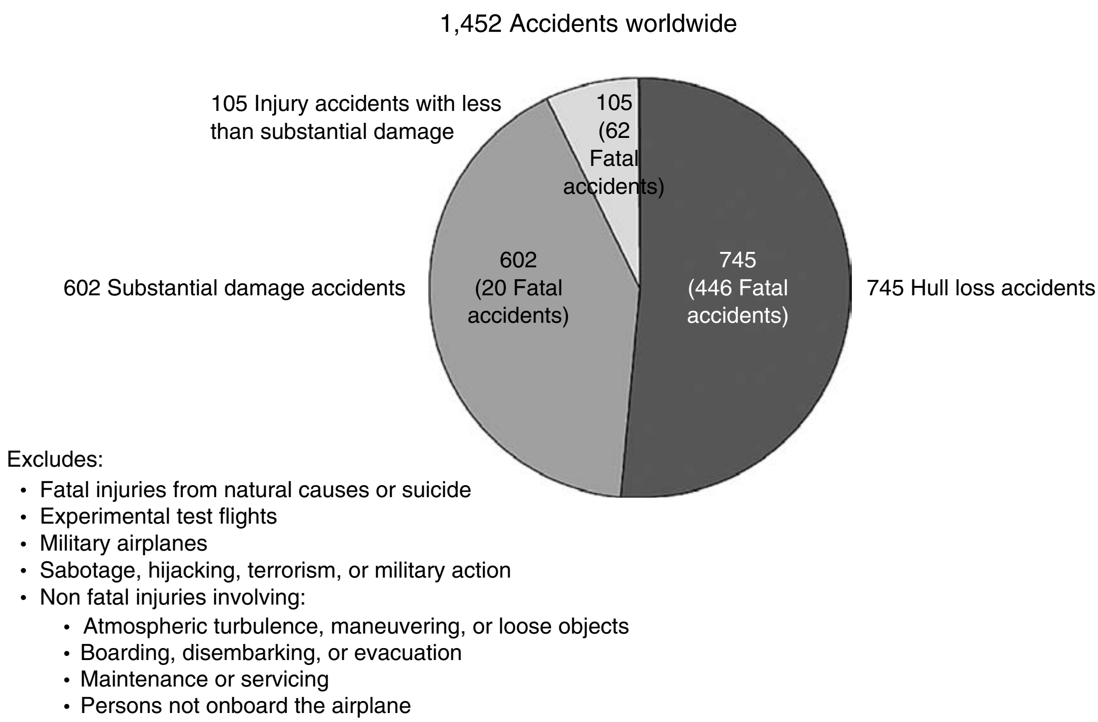


FIGURE 25-3 Accident summary by damage and injury, 1959 to 2005 (Boeing safety data, May 2006).

TABLE 25-1

National Transportation Safety Board 2004–2005 U.S. Transportation Fatalities

Type of Transportation	*2004*	[a]*2005*
Highway		
Passenger cars	19,192	18,440
Light trucks and vans	12,674	12,975
Pedestrians	4,675	4,881
Motorcycles	4,028	4,553
[b]Pedalcycles	727	784
Medium and heavy trucks	766	803
Buses	42	48
[c]All other	732	949
Total	**42,836**	**43,443**
[d]Grade crossings	369	356
Rail ([e]Intercity)		
[f]Intercity Trespassers and nontrespassers	584	555
Employees and contractors	29	29
Passengers on trains	3	16
[g]Light, heavy, and commuter rail	200	189
Total	**816**	**789**
Marine		
Recreational boating	676	697
Cargo transport	26	12
[h]Commercial fishing	42	41
Commercial passengers	21	19
Total	**765**	**769**
Aviation		
General aviation	558	562
Airlines	14	22
Air taxi	64	18
Commuter	0	0
[i]Foreign/unregistered	16	14
Total	**652**	**616**
Pipeline		
Gas	18	17
Liquids	5	2
Total	**23**	**19**
Grand total	**45,092**	**45,636**

[a]Numbers for 2005 are preliminary estimates. Aviation data from NTSB, marine data from Department of Homeland Security, all other data from DOT.

[b]Includes bicycles or other cycles.

[c]Includes vehicle occupant fatalities in other vehicle types, for example, farm or construction equipment.

[d]Grade crossing fatalities are not counted as a separate category for determining the grand totals because they are included in the highway and rail categories, as appropriate.

[e]Data reported to Federal Rail Administration FRA.

[f]Includes persons on railroad property with and without permission. Does not include motor vehicle occupants killed at grade crossings.

[g]Data reported to the FTA. Fatalities for commuter rail operations may also be reported to the FRA and may be included in the intercity railroad fatalities.

[h]Refers to only operational fatalities.

[i]Includes non-U.S. registered aircraft involved in accidents in the United States.

per year of 1 out of 2,067,000, and an exposure risk of 1.9 deaths per 100 million aircraft miles.

Accident rates for all types of operations are available from the FAA, NTSB, and the Bureau of Transportation Statistics websites but are usually 1 to 2 years out of date. The most recent data are usually preliminary and subject to change. A variety of exposure measurements are used in the transportation industry, including time, distance, passenger-distance product, and takeoffs and landings. There is no consensus regarding common denominators of exposure, but the most often quoted rates employ 100,000 hours of flight time or 100,000 departures. Depending on the choice of an exposure denominator for risk calculations, one can get varying results. Some estimates of flying hours are indirect, using a proxy such as fuel receipts, surveys of fixed base operators or, are more direct with the use of a voluntary pilot survey. There is a great deal of variation in these methods and some recent government attempts have been launched to obtain a better measurement of these needed indices that will be of particular importance in general aviation operation estimates. Even in the presence of better exposure data it is important to consider the choice of the measurement method because the perception of the level of safety of any given aviation operation can be made to vary as different methods are employed. To be able to evaluate the effect of changes in the aviation regulatory environment, one must consider carefully the analytic methods that will perform the best in visualizing the effect of the changes. As an example of a useful statistical analysis there is a technique called *segmented linear regression* to examine trend data of active pilots. In one paper in 1988, several risk metrics were examined graphically, critiqued, and compared. The risk metrics examined included:

- Fatalities per hour of exposure to air transportation
- Passenger fatalities per 100 million scheduled passenger miles
- Fatal accidents per 100,000 flights
- Probability of being killed in an air carrier accident
- Total accidents per 10 million system flying hours
- Miles flown between successive accidents and
- Mean time between failures

The paper concludes that there is no unique or correct way of measuring risk in air transportation, and that risk studies should state the applicability, spectrum, and limitations of the chosen risk metrics (5).

An interesting visualization for the purposes of communicating risk perspectives was published in Scientific American in July 2003 from the work of Slovic, Weber (2002) which was itself based on a publication by Slovic in Science in 1987 (http://www.ldeo.columbia.edu/chrr/documents/meetings/roundtable/white_papers/slovic_wp.pdf).

Figure 25-4 shows a risk space in two dimensions, with a vertical axis of the perception of how observable, or known the risk is, and a horizontal axis that depicts the perception of how controllable or dangerous the perceived consequences of the event are. General aviation and commercial aviation are in the lower right quadrant of the graph that was the result of his study of the public perception of risk. Note that in his graph the public perception of aviation is quite dangerous and uncontrollable considering the other activities shown

TABLE 25-2

Risk Comparison from the Department of Transportation (DOT) Office of Hazardous Materials Safety. A Comparison of Risk Accidental Deaths—United States—1999–2003

Type	*5-Yr Average*	[a] *General Population Risk per Year*	*Risk Based on Exposure or Other Measures*
[b] Motor vehicle	36,676	1 out of 7,700	[c,d] 1.3 deaths per 100 million vehicle miles
[e] Poisoning	15,206	1 out of 18,700	
[f] Work related	5,800	1 out of 49,000	4.3 deaths per 100,000 workers
[b] Large trucks	5,150	1 out of 55,000	2.5 deaths per 100 million vehicle miles
[b] Pedestrian	4,846	1 out of 58,000	
[e] Drowning	3,409	1 out of 83,500	
[e] Fires	3,312	1 out of 86,000	
[b] Motorcycles	3,112	1 out of 91,500	31.3 deaths per 100 million vehicle miles
[g] Railroads	931	1 out of 306,000	1.3 deaths per million train miles
[e] Firearms	779	1 out of 366,000	
[h] Recreational boating	714	1 out of 399,000	5.6 deaths per 100,000 registered boats
[b] Bicycles	695	1 out of 410,000	
[i] Electric current	410	1 out of 695,000	
[j] Air carriers	[k] 138	1 out of 2,067,000	1.9 deaths per 100 million aircraft miles
[l] Flood	58	1 out of 4,928,000	
[l] Tornado	57	1 out of 5,015,000	
[l] Lightning	47	1 out of 6,061,000	
[m] Hazardous materials (HAZMAT) transportation	12	1 out of 23,350,000	4.2 deaths per 100 million shipments

[a] An average of approximately 285,000,000 over the period was used in computations.

[b] *Traffic Safety Facts 2004*, Department of Transportation's National Highway Traffic Safety Administration. Motor vehicle fatalities are limited to occupant fatalities and exclude related fatalities to pedestrians, bicyclists, and others. On average, including fatalities to other than motor vehicle occupants in motor vehicle accidents would add approximately 5,500 fatalities to the motor vehicle fatality total. Large trucks are defined as having a gross vehicle weight greater than 10,000 pounds. Truck related fatalities are also counted in the overall motor vehicle category. FHWA-RD-89-013, *Present Practices of Highway Transportation of Highway Material*, Harwood and Russell, indicates approximately 5% of truck accidents reported to the FHWA involved trucks carrying hazardous materials. Applying this percentage to overall hazardous materials transportation yields a risk of approximately 260 fatalities related to general truck transportation risk apart from risks related to the particular hazards of the materials themselves.

[c] Deaths per passenger mile should also be considered as a basic risk measure when comparing risks amongst various modes of transportation. As the average number of passengers in an aircraft far exceeds the average number of passengers in a motor vehicle, the passenger mile risk of air carrier transportation is significantly less than that of motor vehicle transportation.

[d] The fatality rate in currently approximately 1.3 fatalities per 100,000,000 vehicle miles in 1999–2003, or approximately 1 fatality per 77,000,000 mi. Another way of looking at this is that if a person drove approximately 770,000 mi in their lifetime (15,500 mi/yr for 50 years), there is approximately 1 in 100 chance that person will die as a result of an automobile accident during their lifetime.

[e] *WISQARS (Web-based Injury Statistics Query and Reporting System) Injury Mortality Reports 1999–2003*, Department of Health and Human Services' Centers for Disease Control and Prevention. Only unintentional fatalities were used in this report. Fire data was limited to fire/flame fatalities and excluded fatalities due to contact with hot objects/substances.

[f] Fatality data obtained from the *Census of Fatal and Occupational Injuries*, Department of Labor's Bureau of Labor Statistics (2003 and 1999–2002)Workforce data obtained from the *Current Population Survey*, Department of Labor's Bureau of Labor Statistics. Workforce risk calculated using the total employed civilian work force.

[g] *National Transportation Statistics*, Department of Transportation's Bureau of Transportation Statistics. Railroad fatality statistics include railroad only fatalities and grade crossing fatalities. Mileage data used was for Railroad System Safety and Property Damage Data.

[h] *Boating Statistics—2003*, United States Coat Guard.

[i] *Injury Facts*, National Safety Council. 2004, 2005/2006, and 2007 editions used to compile data.

[j] *National Transportation Statistics*, Department of Transportation's Bureau of Transportation Statistics. Air carrier data was calculated for all air carriers operating under either 14 CFR 121 or 14 CFR 135. Data used in this comparison was from air carriers operating under 14 CFR 121, which includes large aircraft, and under 14 CFR 135, which includes aircraft with less than 10 seats. Passenger and cargo aircraft are included in both categories.

[k] Other than the persons aboard the aircraft who were killed, fatalities resulting from the September 11 terrorist acts are excluded.

[l] *U.S. Natural Hazard Statistics*, National Weather Service. The National Weather Service is a program of the Department of Commerce's National Oceanic and Atmospheric Administration (NOAA).

[m] Hazardous Materials Incident Data, Department of Transportation, Pipeline and Hazardous Materials Safety Administration. http://hazmat.dot.gov/riskmgmt/riskcompare.htm.

close to the aviation markers. The association of aviation in an area of known, observable, but somewhat uncontrollable area of risk can be contrasted with the objective data that has been collected from many years of accident investigation and prevention.

There is often a disconnect between the measured safety aspects of aviation and the perception among the public and press of the apparent risks involved.

In 1997, the White House Commission on Aviation Safety and Security issued a challenge to the FAA and the

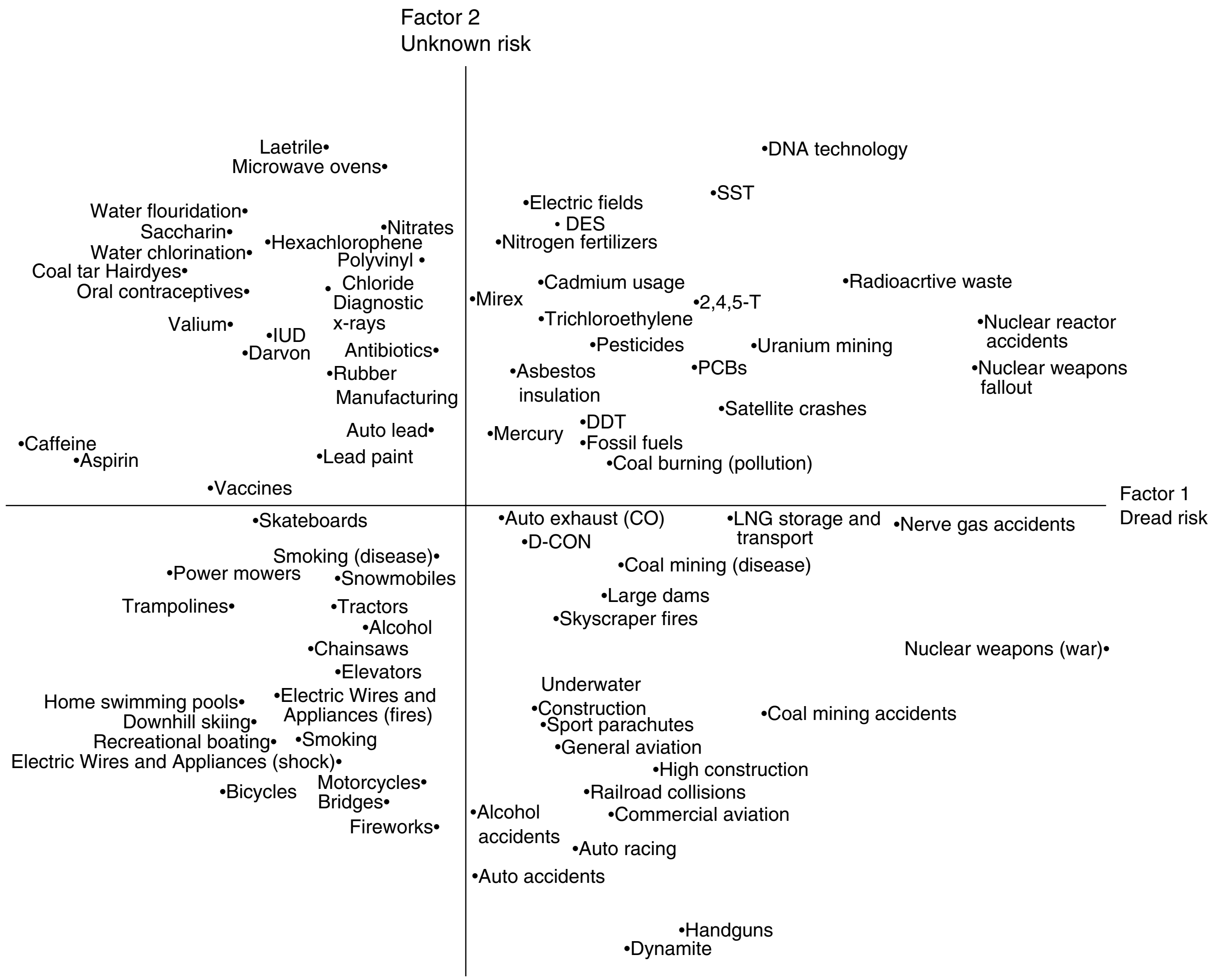


FIGURE 25-4 Risk space perception graph by Slovic 1987. PCB, polychlorinated biphenyls; IUD, intrauterine device; DES, diethylstilbestrol; SST, supersonic transport; DDT, dichlorodiphenyl trichloroethane; CO, carbon monoxide.

aviation industry—to reduce the air carrier fatal accident rate by 80% in 10 years. The 2007 partial data to date reveals a rate of 0.19 fatal accidents per 100,000 departures—a 63% reduction. The draft FAA strategic plan for the period 2008 to 2011 has set goals for safety in the NAS using aircraft departures as the exposure measure:

- Introduce a new performance metric for commercial air carrier safety—fatalities per 100 million enplanements and reduce the current measurement to half by 2025
- Overall aircraft accident rate—reduce the rate per aircraft departure
- Fatalities and losses by type of accident—reduce the number and type of fatalities and losses from accidents that occur for each major type of accident
- Occupant risk—reduce the risk of mortality to a passenger or flight crewmember on a typical flight

(http://www.faa.gov/about/plans_reports/media/Draft_Flight_Plan_06132007.pdf)

DRUG TESTING AND ACCIDENT PREVENTION

On November 21, 1988, the FAA published its final drug-testing rules: *Anti-Drug Program for Personnel Engaged in Specific Activities*. Breath alcohol testing was required a few years later. These rules require operators under the Code of Federal Regulations (CFR) Parts 121 (air carrier) and 135 (commuter/air taxi) to establish antidrug programs for employees (including pilots) who perform safety-related functions (6). More than 500,000 aviation employees are affected by this program, which requires alcohol testing, and urine testing for five commonly abused drugs: marijuana, cocaine, opiates, amphetamines, and phencyclidine (PCP). Testing program results have shown a low rate of positive drug test results in aviation from the beginning of the testing program, especially among flight crews. In 1991, FAA statistics from drug tests conducted on 279,881 aviation employees and job applicants in safety- and security-related positions showed that 0.96% of the test results were positive for drugs of abuse, and in 1992, the rate was 0.95%. Those testing positive included repair facilities workers, contractors, and airline personnel and applicants. The positive rate for airline employees and applicants remained approximately the same in 1991 (0.46%) as in 1990 (0.40%).

Preemployment tests accounted for 49% of the positive results in 1991 and 44% in 1992. Random tests of current employees accounted for the 46% of the positive results in 1991 and 50% in 1992. Return to duty, reasonable cause, and periodic tests, in that order, accounted for the remaining positive results in 1992. There were no positive postaccident test results in 1992, and four in 1991. Positive results from random tests remained below 1% for the third consecutive year. Flight crew accounted for 42 positive results in 1991 and 32 in 1992. By far the largest numbers of positive test results come from maintenance personnel (1,586 in 1991 and 1,598 in 1992). Positive results for both years indicated that marijuana was most prevalent (52% in 1991 and 57% in 1992), followed by cocaine (42% in 1991 and 33% in 1992), amphetamines (4% in 1991 and 4.7% in 1992), opiates (5% in 1991 and 4% in 1992), and PCP (1% in 1991 and 0.7% in 1992). Some persons tested positive for more than one drug. Clearly, progress has been made, and the aviation industry has now been permitted to reduce the random drug test rate to 25% of covered employees.

In the fall of each year, the Federal Register contains a notice published by the FAA Federal Air Surgeon pursuant to 14 CFR Part 121, Appendix I, Section V.C The notice will report the FAA Administrator's decision on whether to change the minimum annual random drug-testing rate based on the reported random drug test positive rate for the entire aviation industry. If the reported random drug test positive rate is less than 1.00%, the Administrator may continue the minimum random drug testing rate at 25%. The notice published in the fall of 2006 contained data from 2005, where the random drug test positive rate was found to be 0.58%. Therefore, the minimum random drug-testing rate was published to remain at 25% for calendar year 2007. Similarly, 14 CFR Part 121, Appendix J, Section III.C, requires the decision on the minimum annual random alcohol testing rate to be based on the random alcohol test violation rate. If the violation rate remains less than 0.50%, the Administrator may continue the minimum random alcohol-testing rate at 10%. In 2005, the random alcohol test violation rate was 0.16%. Therefore, the fall 2006 publication [FR Doc. E6–18726 Filed 11–6–06; 8:45 AM] contained the announcement that the minimum random alcohol-testing rate would remain at 10% for calendar year 2007.

Cases

In July 2006 in Bullhead City, Arizona, a fatal accident with two fatalities and one serious injury during a general aviation operation in a Bonanza G36, was attributed by the NTSB in May 2007 to the pilot's misjudged distance and speed that led to a long landing, and his inadequate recovery from a bounced landing. The accident was due to impairment from alcohol consumption that resulted in an in-flight collision with terrain during an aborted landing attempt. A contributing factor was the FAA's failure to identify existing evidence of substance (alcohol) dependence in the pilot due to an inadequate and incomplete process of screening medical applications (NTSB Identification: **LAX06FA243**).

In Unalaska, Alaska on January 2001, an accident that killed both pilots involved a DC-3 being operated as a nonscheduled air taxi and commuter (14 CFR 135) flight. The NTSB probable cause of October 2002 listed the airplane flight crews' failure to maintain adequate distance/altitude from mountainous terrain during a departure climb to cruise flight, and the captain's impairment from drugs. Factors in the accident were dark night conditions, and the first officer's impairment from drugs. (NTSB Identification: **ANC01FA033**).

In June 2004, in Kodiak Alaska, a fatal accident involving a Beech C-45H Expediter during a nonscheduled air taxi and commuter flight resulted in the NTSB probable cause of September 2005 listing the pilot's failure to follow proper instrument flight rules (IFR) procedures by not adhering to the published missed approach procedures, which resulted in an in-flight collision with tree-covered terrain. Factors contributing to the accident were a low ceiling, fog, rain, and the insufficient operating standards of company management by allowing unauthorized single-pilot instrument flight operations. Additional factors were the pilot's impairment from cocaine, alcohol, and over-the-counter medication for cold, and the FAA's inadequate medical certification of the pilot and follow-up of his known substance abuse problems. (NTSB Identification: **ANC04FA063**).

There are some earlier examples as well. In January 1988, a commuter airliner crashed, killing the 2 crewmembers and 7 of the 15 passengers. The NTSB found that the captain was medically unqualified to serve as a crewmember on the flight due to his use of cocaine before the accident, and that his performance was degraded due to the adverse effects of his use of cocaine before the accident. This degradation was documented as contributing to the accident (7). In 1995, a small cargo aircraft flying under CFR 135 had a fatal crash after the pilot mishandled the engines; the NTSB found the pilot was impaired by the ingestion of alcohol (8). In spite of these cases, the random drug testing of flight crew employees has clearly indicated that they have a very low incidence of positive tests. This has led some analysts to point out the questionable cost-effectiveness of the program. However, the value of such testing as a deterrent has not yet been defined. Medication usage, and particularly alcohol use, remains a significant issue for general aviation. However, private flying operations are not part of the drug-testing program.

AIR CARRIER ACCIDENTS AND SAFETY

During the last decade, there have been two categories of loss of life in worldwide airliner operations that have been associated with the vast majority of airline fatalities. These have been controlled flight into terrain (CFIT) and loss of control in-flight (LOC-I) (Figure 25-5). With CFIT, there is

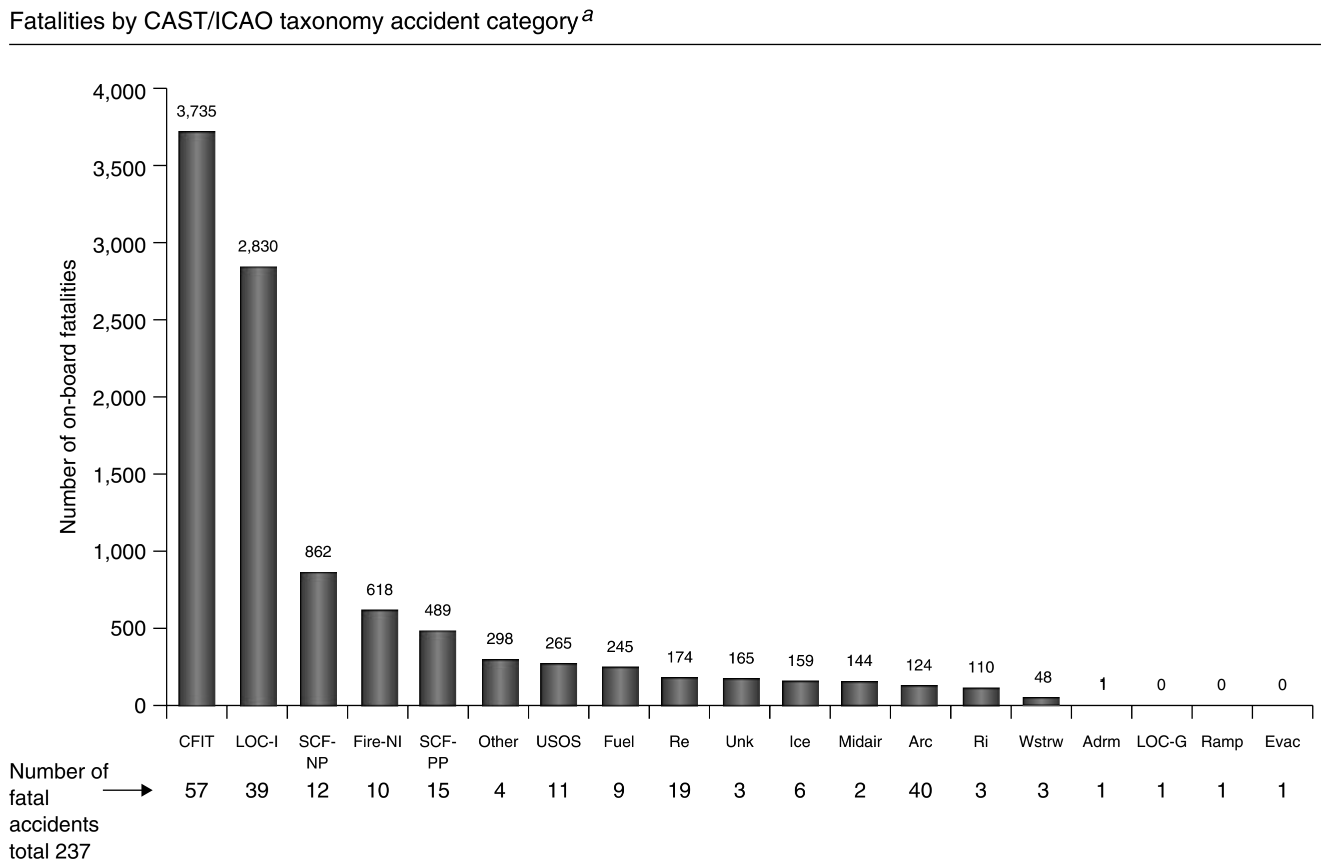


FIGURE 25-5 Worldwide fatal accidents and number of deaths by category of accident, 1987 to 2005. CFIT, controlled flight into terrain; LOC-I, loss of control-inflight; Fire-NI, fire-nonimpact; SCF-NP, system compund failure or malfunction-nonpowerplant; SCF-PP, system compund failure or malfunction-powerplant; RE, runway excursion; Unk, Unknown; ARC, abnormal runway contact; RI, runway incursion; WSTRW, windshear or thunderstorm; Adrm, Aerodrome; LOC-G, loss of control-ground; RAMP, ground handling; Evac, evacuation. (Boeing safety data, May 2006.)

the potential not only for primary prevention, but also of secondary prevention due to survivability and crashworthiness capabilities of large commercial aircraft. Because the impact is controlled, there is some predictability as to the angle of impact, aircraft attitude, and impact forces. The LOC-I, however, can be addressed only by primary prevention. In both cases, human performance issues figure primarily in the accident sequence of events. The response has been to improve pilot training in upset recovery techniques and to install enhanced ground proximity warning systems that give much improved and earlier warning and directional guidance in terrain alerting compared with earlier generation warning systems. The cost, size, and weight have been reduced for these systems to enable their use in commuter and general aviation aircraft. In addition, the Automatic Dependent Surveillance Broadcast (ADS-B) (http://www.ads-b.com/, http://www.adsb.gov/) is a set of technologies pioneered in Alaska with the Capstone project to markedly improve the safety and efficiency of aviation operations.

In Figure 25-6 the general aviation operations are governed under 14 CFR Part 91, the air taxi and the commuter operations are ruled under 14 CFR Part 135. The air carriers operate under 14 CFR Part 121. Business and corporate aviation could be operating under any of Part 91, 135, 121, depending on how they conduct their flight operations. A comparison of the overall annual accident rates per year by type of aviation operation illustrates the large difference between general aviation and scheduled air carrier operations by almost a factor of 10 (Figure 25-6). All of the aviation operations are showing improvement in accident rates over the period 1987 to 2006. The apparent increase in commuter accident rates in the late-1990s is due to a change in the definition and regulation of such operations. In March 1997, the definition of Part 121 operations changed. Before the change, scheduled aircraft with 30 or more seats were operated under Part 121 and those with less than 30 seats were operated under Part 135. After the change, *scheduled aircraft* with ten or more seats were classified as Part 121 operations; therefore, since 1997, most of the larger, turboprop carriers that were once popularly known as *commuters* now operate under Part 121. The regulatory change unmasked the commuter accident rate for the smaller and somewhat less safe unscheduled operators as the largest and safest commuter operators were merged into Part 121 operations. As time has passed, the relatively rapid increase in commuter accident rate was followed by a steady downward trend after the regulatory

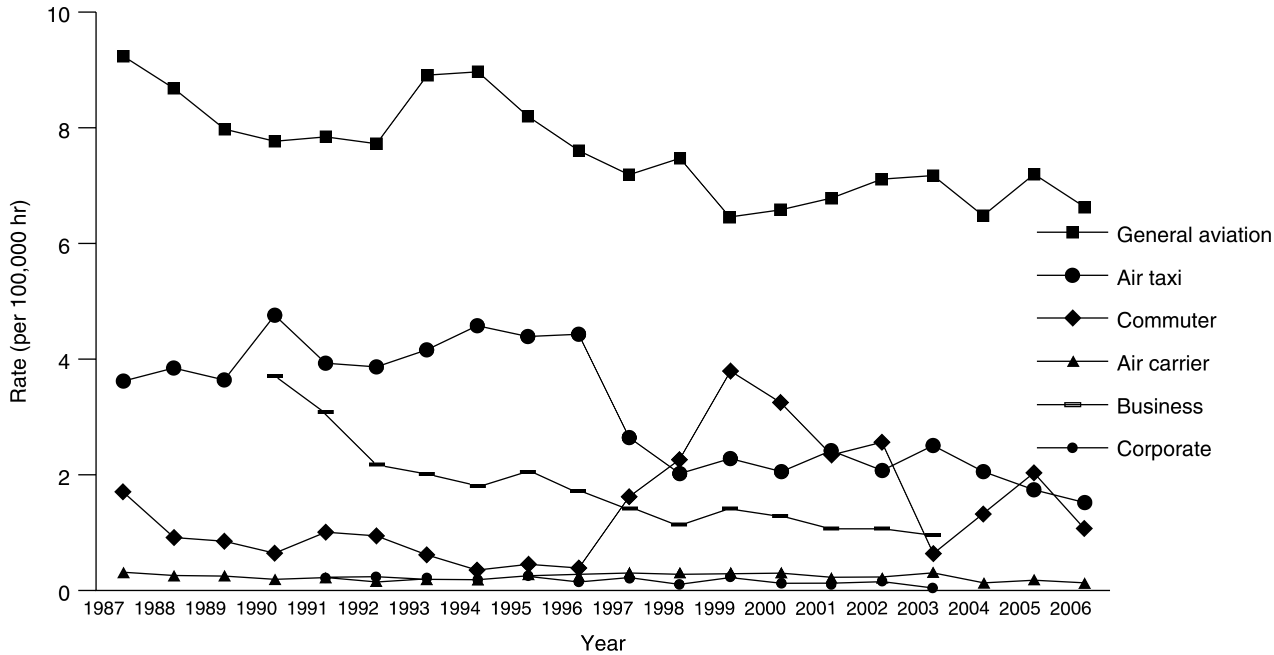


FIGURE 25-6 Comparison of Accident Rates for 1987 to 2006 by type of aviation operation (NTSB, NBAA safety data).

change. Also note that the growth of corporate/executive operations is essentially as safe as the scheduled air carriers. We are currently in a phase where the safety rate of scheduled air operations is the best it has been in aviation history.

AIR CARRIER SURVIVAL FACTORS

Regulations require that before every flight all passengers receive a safety briefing. Although it may be very short for a general aviation flight, airline passengers receive a more extensive and somewhat standardized demonstration by cabin crew or by prerecorded video relating to seat belts, passenger oxygen masks, cushion or flotation device usage, and location of emergency exits. Airline passengers also have a safety information card located near their seat that they are encouraged to read before each flight. Passengers seated in exit rows must meet certain FAA criteria or need to be reseated to ensure that someone sits near the overwing exits who is capable of operating the exits with minimal cabin crew assistance in case of an emergency evacuation of the aircraft. As part of the medical aspects of accident investigation during the postcrash investigation, attention should be directed to such circumstances of the accident sequence or those aspects of the cabin that helped or impeded evacuation of passengers. A survival factors group should be formed to study the consequences of the accident, and to document the successes and failures of the equipment and procedures for dealing with the postcrash environment. Survival factors is a multidisciplinary group comprising evacuation specialists, cabin safety investigators, physicians, flight attendants, and safety engineers, whose investigatory scope should include the items in Table 25-3 according to the NTSB Survival Factors Investigation Checklist and Outline (9).

The NTSB held a public meeting on February 21, 2001, to present safety report NTSB/SR-01/01: Survivability of Accidents Involving Part 121 U.S. Air Carrier Operations, 1983 through 2000. In all accidents involving U.S. air carrier flights (cargo and passenger) operating under Title 14 CFR Part 121, 1983 through 2000, there were 568 total accidents in which 71 accidents (12.5%) were fatal. As related to number of occupants, 51,207 occupants (95.7%) survived, whereas 2,280 occupants (4.3%) died. In 528 (93.0%) out of the 568 accidents more than 80% of the occupants survived. In 26 serious Part 121 accidents (those involving fire, serious injury, and either substantial aircraft damage or complete destruction), there were 2,739 occupants; 1,524 (55.6%) of those occupants survived, 716 (26.1%) died from impact, and 131 (4.8%) died from fire/smoke inhalation. In 12 (46.2%) out of those 26 serious Part 121 accidents, more than 80% of the occupants survived. In 19 of those 26 serious Part 121 accidents that were categorized as *survivable*, 1,523 of the 1,988 occupants (76.6%) survived, 306 (15.4%) died from impact, and 131 (6.6%) died from fire. In 12 (63.2%) of these 19 *survivable* serious Part 121 accidents, more than 80% of the occupants survived.

The report concluded that public perception of survivability may be substantially lower than the actual rate of 95.7% for all Part 121 accidents. Overall 96% of passengers survive all accidents, 56% survive serious accidents, and 77% survive serious-survivable accidents. Finally, Safety Board recommendations to passengers to improve their chances of survival include (a) plan escape routes to more than one exit, (b) pay attention to safety briefings by cabin crew, (c) read

TABLE 25-3

Survival Factors Checklist

Airplane configuration	Including a diagram showing seating configuration, galleys, exits, location of emergency equipment, etc.
Crew and passengers information	Including cockpit, cabin crew, and passenger interviews. Cabin crew interviews should collect information related to seatbelt and shoulder harness integrity before and after impact, difficulties during escape, description of injuries and how they were sustained, how flight crew evacuated the airplane, etc.
Airplane damage and wreckage site	Including description of terrain, site, distance, heading, and relative bearing of ground scars and air conditioning components from main wreckage; description of obstacles/structures struck. Airplane Damage, including description of the airplane damage as it relates to fire pattern, egress, fuselage and wing crush, etc.
Emergency systems	Including the condition of personal announcement system, oxygen equipment, flashlights, first aid kits, megaphones, emergency lighting systems, evacuation alarm system, emergency escape slide, or slide/raft; condition and location of life rafts and life vests.
Evacuation	Including information related to: numbers of doors opened, number of slide/rafts successfully deployed and inflated, development and propagation of fire and smoke, deformation of the cabin, group behavior during the emergency, operation of the emergency floor lighting, operation by the crew of their protective and safety equipment, functioning and coordination of the cabin crew in the emergency, configuration of the seats, functioning of the fire-blocking materials, aisle widths, access to and capability of the exits to allow passengers to exit the aircraft.
Medical and pathological information	Including a summary of injury sustained (fatal, serious, minor, none and total, according to NTSB 49 CFR 830.2 Definitions) as well as a general description of the survivors' injuries. Postmortem examinations: • Each crewmember must be positively identified • Postmortem examinations should be made on each cockpit occupant • Postmortem examination should be made on flight attendants, passengers, and persons on the ground as the circumstances of the accident indicate • Gross injury descriptions should include all fractures, dislocations, lacerations, amputation, burns, and condition of clothing • Toxicologic and microscopic examinations should be performed on all cockpit occupants, selected flight attendants and passengers, and other selected victims as the situation warrants
Emergency Response	Including search and rescue (SAR) information, Aircraft rescue and fire fighting (ARFF) response: • Dispatch and Communications, Fire Suppression, and Rescue Activities • After action activities Law enforcement response, medical response, disaster preparedness, and airport certification

safety briefing cards provided at each seat, and (d) follow crew instructions (4).

GENERAL AVIATION ACCIDENTS AND SAFETY

Safety records from 1938 to date chronicle almost 70 years of general aviation having an improving safety record with approximately an 18-fold decrease in total accident rate. The decline in the fatal accident rate for general aviation has been slower with perhaps a ninefold decrease over the same time period. The last 20 years show a slower decline in the United States (Figure 25-7) with a 26% decrease in the total accident rate and a 20% decrease in the fatal rate. The General Aviation Manufacturers Association maintains some general aviation data for other countries on their website (http://www.gama.aero/home.php). Although all forms of aviation operations will benefit from improved crashworthiness and accident prevention, the greatest number of lives lost in aviation is still in general aviation operations; therefore there is a need to concentrate safety resources on general aviation safety research to continue the improvement in the accident rate.

GENERAL AVIATION ACCIDENT PREVENTION

The efforts of the FAA Office of Aerospace Medicine to initiate an extensive education program for general aviation pilots regarding medical factors of accident prevention almost three decades ago do contribute to the improving GA accident rate in Figure 25-7. This educational program included significant safety enhancements through a nationwide effort to draw attention to the common causes of accidents and in particular the medical and human factors aspects common to mishaps. In this program, general aviation pilots

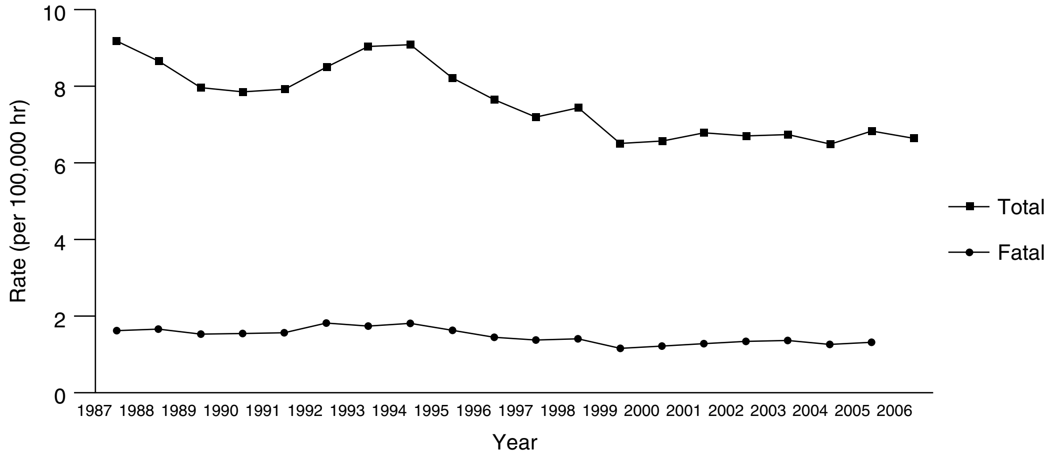


FIGURE 25-7 General aviation accident data for 1987 to 2006 from the General Aviation Manufacturers Association (FAA and National Transportation Safety Board data).

were made aware of the effects of hypoxia as well as other safety information usually taught to military pilots by the use of military hypobaric chambers and crews. Many thousands of private and commercial pilots have participated in this training. As FAA flight standards and Air Traffic Control (ATC) accident prevention procedures were added to the curriculum, the interest increased, and this regional recipe for accident prevention through education was provided nationwide. Currently, every FAA general aviation district office or flight standards district office has an accident prevention specialist (APS). The practitioner of aviation medicine can obtain valuable assistance through the services of the APS, who has excellent teaching aids, including a Barany chair to demonstrate the greatest single cause of fatal general aviation accidents, spatial disorientation. Excellent aeromedical teaching materials for the FAA AME are also available from the FAA's CAMI at Oklahoma City and these materials have been disseminated to many other countries (http://www.faa.gov/pilots/training/airman_education/).

GENERAL AVIATION CRASHWORTHINESS

Most aviation fatalities and serious injuries occur in general aviation operations. *Serious injury* refers to any injury that meets the following criteria (1):

1. Requires hospitalization for more than 48 hours, commencing within 7 days of the date of receiving the injury
2. Results in a fracture of any bone (except simple fractures of fingers, toes, or nose)
3. Causes severe hemorrhages, nerve, muscle, or tendon damage
4. Involves any internal organ
5. Involves second- or third-degree burns, or any burns affecting more than 5% of the body surface

In examining accidents in one decade alone, more than 100,000 occupants were injured in approximately 40,000 accidents. Of these accidents, 17.7% involved at least one fatality. The NTSB accident investigators report that few changes have been made in cabin interior design or restraint systems, which might have eliminated or reduced these injuries. Sharply contrasting with this is the progress in improving air carrier and automobile crashworthiness. Automobile accidents have only one fatality for every ten serious injuries, whereas general aviation aircraft accidents produce two fatalities for every three serious injuries. Aircraft impacts have greater speeds and therefore have much more energy to dissipate, because energy is proportional to the square of the speed.

The NTSB acknowledges that automotive and aircraft accident statistics are not directly comparable because of the higher speeds and many different crash loads and vehicle design objectives in aviation. The NTSB references to crashworthiness remark that when crash forces transmitted to occupants through properly designed seats and restraint systems do not exceed the limits of human tolerance to abrupt deceleration, and when the cabin structure remains sufficiently intact to provide a livable space immediately around the occupants, crew and passengers should survive the accident without serious injury (10,12). The postcrash environment may contain other lethal potentials such as drowning or weather-related hazards that the pilots and their passengers may have to surmount. Therefore, survival training for wilderness exposures is a reasonable precaution that all pilots should undertake.

In an effort to improve crash survivability through crashworthy design, engineers developed the "CREEP" concept (see subsequent text). Crashworthiness is defined as the ability and technology of an aircraft and its internal systems and components to protect occupants from injury in the event of a crash. In other words, crashworthiness does not prevent the accident from happening; it rather mitigates the effects of the impact and therefore changes favorably the injury outcome.

Hugh DeHaven is considered to be the "father" of crashworthiness for his work in protective design and injury biomechanics at Cornell University Medical College in the early 1930s. He started the viewpoint that "airplane crashes should be studied from the point of view of accident pathology and injury causes" (13). He also conducted the combined engineering and pathological review of natural experiments from attempted suicide jumps from 50 to 150 ft in survivors. Impact velocities, stopping distances, and estimates of impact forces were closely determined, providing valuable data to his crash injury research.

The acronym "CREEP" has been used as a systematic tool to organize the important aspects/factors of crash survivability as follows:

C = Container, related to the occupants' "living space" during the impact
R = Restraint, dealing with restraint systems and equipment provided to crew and passengers
E = Energy absorption, directly related to the deceleration forces transmitted to the occupants through the aircraft structures
E = Environment, related to the "internal" surrounding environment of crew and passengers
P = Postcrash factors, mostly related to the rapid evacuation of the aircraft and the postimpact conditions such as fire, water, and hostile terrain

A detailed analysis of these factors is beyond the scope of this chapter; however, it is worth mentioning the similarities to the epidemiologic approach postulated by William Haddon Jr. The Haddon Matrix was developed in an effort to develop a strategy for injury identification and control. Such a matrix "provide(s) a means for identifying and considering, cell by cell: a) prior and possible future allocations and activities, as well as the efficacies of each; b) the relevant research and other knowledge—both already available and needed for the future; and c) the priorities for countermeasures, judged in terms of their costs and their effects on undesirable injury results, that is on the problems to be reduced" (14). In its simplest form, the matrix has two dimensions: The first is what Haddon called *phases*. In the case of aircraft accidents, the phases are "precrash," "crash," and "postcrash." The second dimension of the matrix is divided into three *factors*: the "human," (or host, i.e., the person susceptible to injury; the specific agent), the "vehicle" (or "vector" transferring the mechanical energy), and the "environment" (which can be subdivided into "physical" and "sociocultural").

Because of the volume and complexity of data in aircraft accident investigation, it is necessary to develop a database system to process and analyze injury data in a meaningful way. The Haddon matrix might be successfully used for the purpose of evaluating intervention measures aimed to reduce injuries if sufficient detailed injury data was gathered from accident investigations. This information is not currently collected in detail apart from the major accident investigations involving the Washington based go-team investigations, where a Survival Factors group is formed.

To determine an injury pattern, it is necessary to correlate injury information with the following basic information: (15).

1. The impact forces (direction and magnitude of accelerative forces)
2. The time, duration, and direction of the applied forces
3. The cockpit or cabin configuration
4. The nature of the accident and subsequent occurrences and
5. The occupant kinematics in the accident, particularly relating to restraint systems and evacuation methods

In addition, during impact there are simultaneous rotational and translational movements of the different body parts (i.e., head, neck, thorax, abdomen, and upper and lower extremities). The biodynamics of these moving body parts during impact forces are very complex and not well understood (16). Collection and analysis of good quality injury data in real aircraft accidents and modeling with slide crash test data should answer questions concerning injury patterns. For example, a detailed evaluation of seat damage, including cross validation using injury data has been proposed. Seat structural performance can indicate the appropriateness of existing dynamic test severity levels and can assist investigators in estimating crash severity. In addition, injury patterns can be used to evaluate the adequacy of occupant injury assessments made during dynamic tests. Integration of seat structural performance and injury data is crucial to form a basis for developing new safety standards and refining existing standards (DeWeese R, *personal communication*, 2006, FAA CAMI).

The unique nature of injury data constitutes a real challenge to injury researchers in reference to methodological issues, etiology, and the impact of interventions in the field of injury prevention and control (14,17). Some examples of the complicated characteristics of injury data are summarized as follows:

- Injuries occur in the context of a sudden transfer of physical energy, either mechanical, thermal, radiant, chemical, or electrical. In the case of aircraft accidents, moving objects are vehicles of mechanical energy.
- Injuries might occur more than once to the same individual.
- A single event such as an aircraft accident might result in multiple types of injuries to multiple body sites with different severities.
- Knowledge, attitudes, and behaviors play a major role in determining the etiology of injury.

Determining the mechanisms of injuries is a critical step in developing injury prevention and mitigation strategies in aviation accidents. Developing a research-oriented database to categorize and classify injury outcome in aircraft accidents is the next step needed to answer fundamental questions related to injury causation (18).

In Section 23.785 of 14 CFR Part 23, as amended by Amendment 23–19, effective July 18, 1977, the FAA required shoulder harnesses (front seat) for all normal, utility, and acrobatic category airplanes for which an application for a type certificate was made on or after July 18, 1977. It also requires all small civil airplanes manufactured after July 18, 1978 to have an approved shoulder harness for each front seat. In FAA policy statement, ACE-00-23.561-01, regulatory guidelines for the approval of the retrofit of older aircraft with shoulder harnesses have been published. The advent of airbags being incorporated into aviation restraint systems is becoming very widespread and most new aircraft are sold with this option. The investigator should be aware of Advisory Circular AC 21-34, Shoulder Harness–Safety Belt Installations, June 4, 1993.

An older study ending in 1952 still holds valuable lessons because there are many general aviation aircraft that still utilize older style restraint systems. The study reported that of 913 accidents involving 1,596 occupants and 15 aircraft models, there were 389 fatalities, and that "roughly one third of the 389 people that were killed . . . died unnecessarily."

The most common deficiencies in general aviation aircraft are as follows:

1. Lack of adequate upper torso restraint. Head injuries remain the most frequent injury as well as the major cause of death and serious trauma. This usually occurs when the occupant jack-knifes over the seat belt and contacts hard, sharp, unyielding, or rigid structures.
2. Inability of seats to adequately attenuate vertical compressive forces. Recent attention has been given to improved design of the front seats, but the rear seats do not appear to provide equivalent protection.
3. Lack of adequate seat support and attachment. Even with upper torso restraint and attenuated vertical compressive forces, an inadequately supported and attached seat will reduce injury tolerance.
4. Cabin interiors that contain many lethal surfaces, structures, and objects that cause death or serious trauma upon crash impact. Flailing appendages, even when upper torso restraints are worn, can contact controls and nonyielding structures.

An FAA report states that, "Severe but nonfatal injuries were common in 3 to 5 G accidents. Fatalities and very severe injuries occurred in crash decelerations of 6 to 10 G. At 10 G and above, most present general aviation aircraft disintegrate to the extent that the value of restraint equipment for crash survival is doubtful." In contrast, a new-generation agricultural aircraft was manufactured, patterned after a prototype aircraft with a 50-G seat, an integral double upper torso restraint with inertial reel, a 40-G cockpit box, the storage hopper placed between the engine and the pilot to provide energy absorption, and an overturn structure (roll bar). In a 10-year period, these aircraft were in 368 accidents with only 3% fatalities, whereas for the same period, the fatality rate in all U.S. general aviation aircraft averaged 12.8%. If all occupants wear shoulder harnesses, fatalities might be reduced by 20%. Of seriously injured persons in survivable crashes, 88% are expected to experience significantly fewer life-threatening injuries if shoulder harnesses are worn. Thirty-four percent of the seriously injured occupants of survivable accidents are expected to be less seriously injured if energy-absorbing seats are available (10,12).

Flying as either a passenger or crewmember is associated with a measurable degree of risk. This risk has continued to decrease as accident prevention, protection, and survival is improved. If government, manufacturers, airport personnel, crews, and passengers continue to contribute to, and use, the knowledge, equipment, training, and information available, the probability of survival is excellent should an accident occur. Professor Jim Reason developed a model of human error that at its center states that although the expression of human error seems almost infinite in variety, it actually reduces down to several overall categories of errors, omissions, and mistakes. His other important insight was that the sequence of events that link up together to result in an accident can span many scales of time and that there are some latent or hidden deficiencies in aerospace systems that may contribute in unexpected ways to the causation of accidents. There are a number of barriers preventing an accident, each capable of trapping a sequence of events that otherwise would lead to an accident. These barriers stack up in layers and because there are no perfect safety programs there are "holes" in each layer of accident prevention or safety layer. This is why the model is also known as *Reason's Swiss cheese model of human error* (19). Aviation accidents are rare because the complex system of aerospace operations has multiple layers of safety; therefore, while deviations, mistakes, and failures may not be all that rare, it is extremely rare that a sequence of events (or misevents) can proceed all the way to an accident occurrence. Each of these layers is "peopled" by the various individuals in aviation, from the owner/operator of the aviation enterprise, through the regulatory and inspection authorities, the aircraft designers, manufacturers, mechanics, dispatchers, air traffic controllers, flight attendants, and pilots. Therefore everyone in aviation, in each layer, can alter the chain of events as described by Reason's human error, and can prevent accidents. The aerospace medicine practitioner has several opportunities to actively intervene in and contribute to aviation operations to prevent accidents. These include being a source of education for aircrew regarding aviation stressors, aerospace human factors and by providing proper medical certification of pilots. When an accident or incident occurs, aerospace medical practitioners also have many skills to offer to the investigation of the sequence of events that culminated in the accident or incident.

MEDICAL AIRCRAFT ACCIDENT INVESTIGATION TECHNIQUES

Aircraft accidents are not new occurrences. With the first flights of humans came the first flight accidents of humans.

An accident badly damaged the front rudder frame of the Wright Flyer, cutting short the early flights of Wilbur and Orville Wright in the first successfully controlled, powered, and manned heavier-than-air machine near Kitty Hawk, North Carolina, on Thursday, December 17, 1903. Analysis of accidents leads to continued improvement and refining of aircraft design and the discovery of piloting techniques. Although this chapter uses aircraft accidents to illustrate the techniques for the investigation of accidents, identification of victims, and evaluation of injuries, the methods are directly applicable to accidents involving other modes of transportation.

History

The first reported aircraft fatality in the United States occurred during acceptance flights when Orville Wright took an observer aloft to test a new propeller while demonstrating the Wright Type A Flyer to the U.S. Army Signal Corps at Fort Myer, Virginia, on September 17, 1908. When a crack developed in the starboard propeller of the Flyer, causing violent vibrations and failure of the elevator, the aircraft, from an altitude of approximately 75 ft, impacted the ground (Figure 25-8). First Lieutenant Thomas E. Selfridge, a pilot candidate, aboard as the observer, died as a result of a compound comminuted fracture of the base of his skull during the crash. An autopsy was performed, and Captain H. H. Bailey (Medical Corps, U.S. Army) determined the cause of death. An aeronautic board investigated to determine the cause of the crash and produced a summary report, which interestingly did not address head injury protection. The next pilot candidate, Lieutenant Hap Arnold, began to wear a football helmet to provide some head protection and also pioneered the use of goggles.

On May 6, 1935, Transcontinental and Western Air flight no. 6, with Senator Bronson M. Cutting on board, crashed, killing five persons including the Senator. As a result of this crash, an outraged Senate quickly authorized the Committee on Commerce "to investigate . . . [the Cutting crash] . . . and any other accidents or wrecks of airplanes engaged in interstate commerce in which lives have been lost; and to investigate . . . interstate air commerce, the precautions and safeguards provided therein, both by those engaged in such interstate air transportation and by officials or departments of the United States Government; and to investigate . . . the activities of those entrusted by the Government with the protection of property and life by [sic] air transportation, and the degree, adequacy, and efficiency of supervision by any agency of Government including inspection and frequency thereof . . ." (20). This action established a federal interest in aircraft accident investigations that was initially included in the activities of the Civil Aeronautics Board, which in 1958 became the FAA, and in 1974 an independent body, the NTSB, was mandated by Congress to determine the probable cause of all transportation accidents, and to

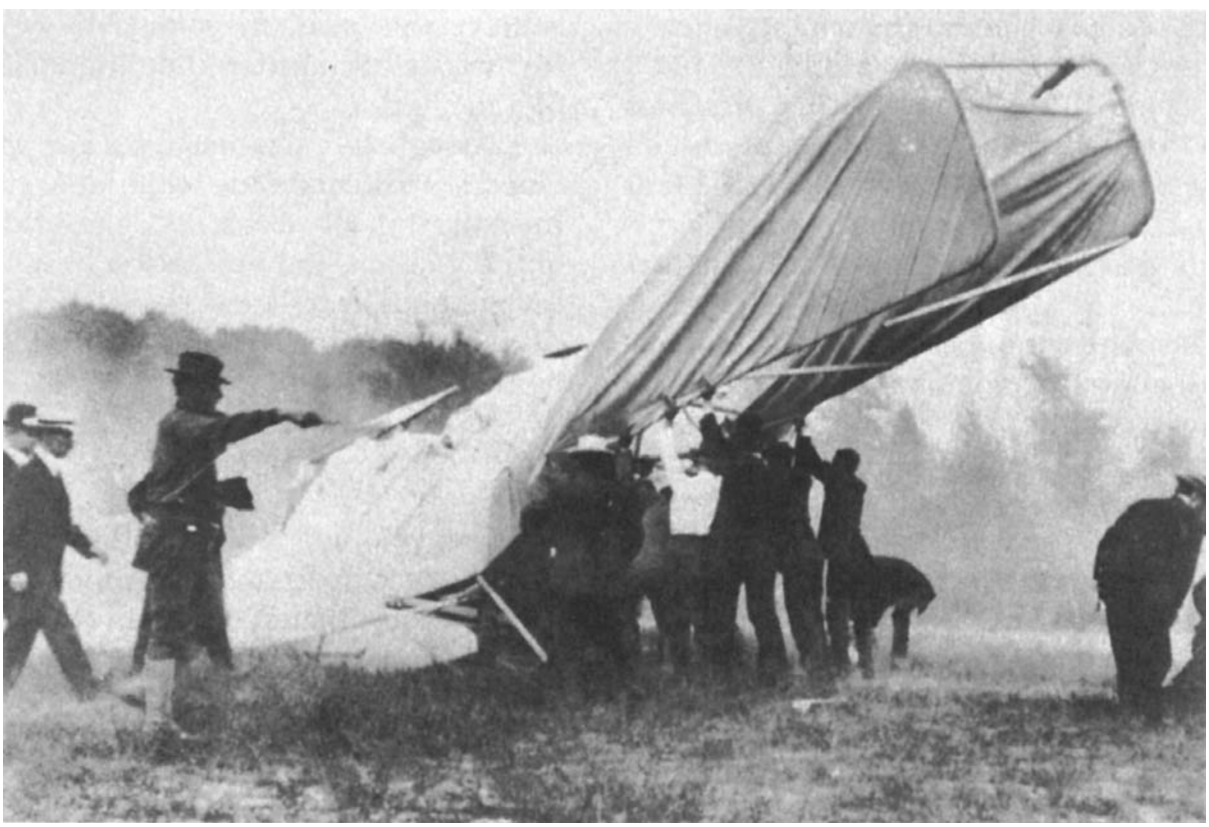


FIGURE 25-8 Crash of the Wright Flyer at Fort Myer, Virginia, on September 17, 1908 (photo courtesy of Armed Forces Institute of Pathology).

make safety recommendations to the regulating agencies and industry.

Although investigation into the mechanical causes of crashes progressed, and medical expertise accumulated during the World Wars I and II, it was not until the 1950s that the value of medical investigation of aircraft crashes became apparent. Several well-publicized and seemingly mysterious crashes of jet-powered British Comets, the first jet-powered commercial passenger aircraft, led to medical investigations that marked the beginning of modern aeromedical pathology, which we now call *aerospace pathology*. The investigations dispelled the sense of mystery regarding passenger jet transportation by providing thorough and scientific explanations for the sequence of events and the correlation of the postmortem findings with the flight environment and aircraft structures. One Comet crashed on January 10, 1954, with 35 persons on board approximately 25 minutes after taking off from Rome *en route* to London. Another Comet crashed *en route* to Cairo from Rome on April 8, 1954, with 21 persons on board. Both planes crashed at sea, and there were no immediate indications as to the cause. Postmortem examination of the remains of the passengers and crew who floated to the surface allowed pathologists to determine that an explosive decompression had occurred in these pressurized cabins. This structural failure resulted from insufficient hull strength to withstand the pressure differential between the cabin and the outside atmosphere at altitude due to the repetitive stresses of flight leading to metal fatigue (21).

The greatest loss of life in an aviation mass disaster was the collision of two Boeing 747 jumbo airliners at Tenerife in the Canary Islands on March 27, 1977. The 583 fatalities required a large and multinational, multidisciplinary response (Figure 25-9). This accident focused attention on the problems that aircraft accidents and other mass disasters can present and was partly responsible for the development of a human factors focus on crew resource management. One of the authors of an earlier version of this chapter, Dr Robert R. McMeekin was involved in the on-scene investigation.

ORGANIZATION OF THE INVESTIGATION

International Civil Aviation Organization Guidelines

Investigations are performed using ICAO's "International Standards and Recommended Practices, Aircraft Accident and Incident Investigation," which is Annex 13 to the convention on International Civil Aviation. The guidelines are available on the Internet (www.icao.org).

The use of a multidisciplinary team approach to accident investigation leads to coordinated efforts in the following general groups of investigators: operations, structures, power plants, human performance, survival factors, medical factors, aircraft systems, witnesses, ATC, weather, flight data recorder (FDR)/cockpit voice recorder (CVR), maintenance records, airport rescue, and firefighting. Other groups are formed as necessary to deal with particular aspects of the investigation, and sometimes one group subsumes another group's function and members.

Multidisciplinary Team Constitution

Modern investigations vary in their complexity and the need for specialized team members. In general, it is advisable to have identified, before an accident, individuals and organizations that are able to provide expertise to the investigation in a variety of specialized disciplines. Increasingly, multidisciplinary team makeup is necessary to deal with aviation disaster management and investigation. Forensic pathologists are essential to the documentation of the cause of death and injury patterns that will be learned from the autopsies. Aerospace pathologists will bring additional expertise to bear in survival factors investigations, and clinicopathologic correlation of the observed deaths and injuries. Forensic anthropologists are useful in bone fragment identification and classification. Forensic odontologists provide essential dental identification expertise for the on-scene phase of the investigation. DNA specialists and teams have become the standard in providing positive

FIGURE 25-9 Wreckage of two 747 airliners on the runway at Tenerife, Canary Islands, on March 27, 1977 (photo courtesy of Armed Forces Institute of Pathology).

identification of fatalities, especially in high-impact crashes where large numbers of body fragments are recovered. Aerospace medicine specialists, particularly if they are also pilots, contribute their knowledge of aviation medicine, as well as human factors, pilot skills, and the impact of medical factors on human performance. Aviation human factors psychologists bring essential skills in understanding human performance in areas of pilot cognition, ergonomics, and in using specialized techniques such as voice stress analysis. An image specialist with training in aircraft accident investigation can provide essential documentation using print, slide film, and videotape, as well as digital media. This team member frees up the other specialists to deal with their specific involvements. Some areas overlap, and not all disciplines are available for every accident.

The NTSB will designate one or more team members representing the various qualified parties of the investigation to be assigned to each of these areas, but the actual composition of the accident investigation team always depends on the circumstances of the accident and the number of people involved. For example, human factors, survival factors, and medical factors teams may be combined or maintained separately. The survival factors/medical factors group considers the crashworthiness aspects of the investigation, with particular emphasis on organization, identification, injury tolerance, and analysis of injury patterns, and also deals with the morgue and the local jurisdiction. The human performance group examines factors that affect the performance of the flight crew, mechanics, and air traffic controllers, and their investigation evaluates the cognitive, ergonomic, and psychological factors that may have contributed to the accident. All these specialized groups' observations are the basis of recommendations for changes in standards for training, medical certification, and selection of the various professions. They also lead to improvements in cockpit or passenger compartment layout and the design of avionics, seats, restraints, protective equipment, and escape mechanisms and pathways. More recently their observations have implications for organizational inputs to accident causation by highlighting supervisory and organizational aspects of airline operation and regulation that may have contributed actively or latently to the chain of events leading up to the accident.

Jurisdiction

The jurisdiction to conduct investigations of deaths usually rests with the government of the territory in which the death occurs. Treaties, conventions, and executive agreements resolve many of the problems that result from differences in laws among countries. The 1944 Chicago Convention provides for international participation by the state of registry in investigations of civil aviation accidents as follows (22):

> In the event of an accident to an aircraft of a contracting State occurring in the territory of another contracting State, and involving death or serious injury, or indicating serious technical defect in the aircraft or air navigation facilities, the State in which the accident occurs will institute an inquiry into the circumstances of the accident, in accordance, so far as its laws permit, with the procedure which may be recommended by the International Civil Aviation Organization. The State in which the aircraft is registered shall be given the opportunity to appoint observers to be present at the inquiry and the State holding the inquiry shall communicate the report and findings in the matter to that State.

Effective international cooperation resulted when a major air disaster involving two Boeing 747s occurred in Tenerife in the Canary Islands in 1977. U.S. representatives participated in the investigation, and the Spanish government permitted the removal of the fatally injured U.S. passengers from Tenerife to Dover Air Force Base in Delaware for identification.

Jurisdiction disputes also occur at the functional level between government agencies. The NTSB, Federal Bureau of Investigation (FBI), and Department of Defense (DoD) are only a few of the U.S. agencies with an interest in accident investigation. In addition, the Environmental Protection Agency (EPA) is involved, ensuring the cleanup of the accident scene. The Occupational Safety and Health Agency (OSHA) has determined that blood-borne pathogen training is required for accident investigators, on-scene exposures are properly followed up and documented, and that accident investigators be offered vaccination against hepatitis B infection. Although their interests may occasionally be diverse, personnel from the agencies are able to work together harmoniously. Statutes, regulations, and letters of agreement covering most situations clearly define the relationships between the various federal agencies.

In the United States, by virtue of the 10th Amendment to the Constitution, the individual states retain jurisdiction over matters that federal legislation has not preempted. State laws regarding postmortem investigations differ considerably, and the official who authorizes postmortem examinations varies from state to state. Autopsy is available in some states only when this official suspects that a death resulted from unlawful means. The NTSB, FAA, U.S. military services, and armed forces from many other countries recognize the importance of the pathologic and toxicologic investigation of fatal aircraft accidents, and they have published regulations requiring the postmortem examination of all fatally injured crewmembers. With respect to civil jurisdictions, the NTSB routinely obtains an autopsy on pilots and has toxicologic specimens sent to the CAMI for analysis. There are barriers to conducting comprehensive accident investigations, and the result is that many postmortem investigations of aircraft accident fatalities are inadequate.

Adequacy of Investigations

Investigations of aircraft accident fatalities are inadequate or unavailable in certain circumstances because understanding of the federal aims of the investigation and cooperation is lacking. Approximately 90% of U.S. military aircraft accident fatalities occur in areas where the federal government has no authority to obtain postmortem information that may be essential to aviation safety and accident prevention, and where many local officials refuse to fully cooperate with the military investigations. In states without a state medical examiner system, where each county is responsible for death investigation, there is often lack of a qualified staff to deal with a large-scale aircraft mass disaster. Even with smaller scale general aviation accidents, there is often little cooperation.

The primary objective, and the legal responsibility, of the investigating authority is in determining the cause of the accident, as well as documenting the consequences of the accident, including the reasons for death and injury of the crew and passengers. The primary interest, and legal responsibility, of coroners and medical examiners is in determining the cause and manner of death and seldom in collecting information concerning aircraft accident and injury prevention. The authorizing official or examining pathologist may have no interest in aircraft accidents and may have no knowledge, experience, or training in the techniques involved. These officials often conduct only an external description of the body, frequently omitting the microscopic and toxicologic examinations necessary to determine the presence of toxic substances in the aircraft and preexisting disease in the aircrew. Even when local officials have the authority to conduct complete autopsy examinations, they may elect not to perform them. In one instance, in answering a request for information about his investigation after a fatal aircraft accident, a coroner's pathologist responded, "according to local interpretation of state law, a coroner's autopsy precedes to [sic] the cause of death and is not an academic endeavor. When the cause of death is obvious in the gross autopsy, as is usually the case in aircraft accidents, microscopic examinations are not performed." (McMeekin *personal communication,* 1985) In such cases, the military must depend on local civilian officials to conduct whatever examinations they deem advisable.

Even the presence of trained forensic pathologists with experience in investigating aircraft accidents does not ensure adequate examinations. Statutory authority often limits even these trained investigators in the scope of postmortem examinations. Most coroners and medical examiners do not have sufficient funds or staff to permit the more than 2 workdays often needed for a thorough investigation. Situations in which it is not clear who, if anyone, has jurisdiction are especially disconcerting because nothing is accomplished, although everyone agrees that postmortem examinations are needed. In the above-mentioned major air disaster involving two Boeing 747s at Tenerife, there were 583 fatalities, of which more than half were U.S. citizens. Of the 396 persons aboard the Pan American aircraft, 334 died. The jurisdiction of Spain to investigate the accident, and of the United States to participate, was clear under the provisions of the Chicago Convention. Logistics, however, necessitated the removal of the U.S. fatalities to Dover Air Force Base, where easier access to communications facilities aided the identification process. Detailed postmortem examination could have determined the exact cause of death and why so few survived this ground collision, but no one established the jurisdiction to conduct complete autopsy examinations. Without these examinations, the investigation was incomplete. The state of Delaware could not give adequate authorization for postmortem examinations because the deaths did not occur in Delaware. The NTSB did not have jurisdiction because Spain was in charge of the investigation. Everyone agreed that the investigations were necessary, but no one could cite a proper authority. The result was that the investigators used only those methods necessary to establish the identity of the bodies. Valuable information was lost that could have contributed to the furtherance of air safety.

Disaster Mortuary Operational Response Team

The Disaster Mortuary Operational Response Team (DMORT) is a federal-level response team designed to provide mortuary assistance in the case of mass fatality and cemetery-related events such as flood damage to a cemetery. The United States Public Health Service (USPHS) and the Office of Emergency Preparedness-National Disaster Medical System, along with thousands of volunteers from across the country dedicated to helping those in need, sponsor this and other medical teams. The Family Assistance Act of 1996 created a new division within the NTSB called the *NTSB Family Affairs Division*, which is charged with helping local authorities to coordinate victim identification and family assistance. The NTSB has agreements with DMORT and other national entities that assist them in fulfilling their duties under this law. A memorandum of understanding between the NTSB and USPHS gives the NTSB and its Family Affairs Division the ability to request DMORT for all transportation accidents involving multiple deaths.

Federal Interest in Aircraft Accident Investigation

Congress has expressed an interest in the investigation of aircraft accident fatalities. The Federal Aviation Act of 1958, enacted on August 23, 1958, established the FAA. Other laws, notably by the Department of Transportation Act of 1967, subsequently amended this basic enabling legislation. On July 5, 1994, Public Law 103–272 recodified certain laws pertaining to transportation. As a result, provisions of Subtitle VII of Title 49, United States Code, superseded the Federal Aviation Act. The 1988 Aviation Safety Research Act, later recodified in Title 49 United States Code (49 U.S.C.), provides a mandate for CAMI to conduct civil medical accident investigations and research. Furthermore, Congress determined that the federal government has an overriding interest in aviation safety and enacted legislation to ensure thorough investigations, including autopsies, of all civil aircraft accidents. The Independent Safety Board Act of 1974 established an NTSB that was separate from the FAA. This act was also later recodified into 49 U.S.C. The NTSB may conduct these autopsies regardless of provisions of local law unless the local laws pertaining to autopsies are based on the protection of religious beliefs, as follows (23):

> In the case of any fatal accident, the Board is authorized to examine the remains of any deceased person aboard the

> aircraft at the time of the accident, who dies as a result of the accident, and to conduct autopsies or such other tests thereof as may be necessary to the investigation of the accident: provided, that to the extent consistent with the needs of the accident investigation, provisions of local law protecting religious beliefs with respect to autopsies shall be observed.

A similar federal interest exists in military aircraft accidents in which the economic effects and impact on national defense are critical, but the authority of the NTSB does not extend to the investigation of accidents involving solely military aircraft. Statutes authorize the U.S. Army and Air Force to conduct autopsies of persons fatally injured onboard military aircraft when a fatal accident occurs on a military reservation where there is sole U.S. military jurisdiction. The military services recognize the importance of postmortem investigations of all fatally injured military crewmembers, and their regulations require autopsy examination regardless of where death occurred. Regulations give military commanders power, similar to that of coroners, to direct the performance of autopsies of aircraft accident fatalities involving military personnel.

The FAA CAMI processes all toxicology samples obtained by the NTSB investigations and maintains an aircraft accident research team to provide multidisciplinary support regarding medical and human factors to the NTSB and the FAA Office of Accident Investigation. The Office of the Armed Forces Medical Examiner, located at the Armed Forces Institute of Pathology (AFIP), and staffed by fully trained forensic pathologists, investigates all fatal U.S. military aircraft accidents. The AFIP also provides consultation and pathology support to the NTSB and other government agencies. Active aviation pathology departments also exist in Germany, the United Kingdom, Spain, and other countries.

Phases of the Investigation

The success of the investigation depends on the degree to which one has prepared before the accident occurs. Usually the investigating authorities arrive after the immediate crash, fire, and rescue response from the affected airport/local community. Therefore, the preservation of life and immediate care of the ill and injured, as would be required in an airport disaster response plan, will not be considered here. The immediate postaccident period may seem chaotic, with many concurrent activities going on, all competing for attention by the medical accident investigator, and experienced investigators recognize the importance of the early development of an organizational plan that considers the following five general phases:

1. Preliminary evaluation
2. Data collection
3. Data analysis
4. Conclusions
5. Recommendations

The NTSB and CAMI have prepared autopsy guidelines for medical examiners to help guide their postmortem examinations. The Joint Committee on Aviation Pathology (JCAP) prepared an outline of six steps for the pathologist to take when investigating fatal aircraft accidents (24). These general steps are useful for participating in survival factor/medical factor investigations. These steps are an adaptation of the five investigation steps listed earlier, and they are useful guidelines for any investigating physician. Although no rigid protocol can describe in detail how to investigate all accident types that a pathologist may encounter, JCAP recommends the following steps for the investigation of injuries sustained by the victims of a crash.

The first step in the investigation is for the pathologist to familiarize himself or herself thoroughly with the type of aircraft, its internal structure, seating arrangement, ejection mechanism, and general layout, and, if possible, to examine an intact plane of the type in question. It is essential to review the location and operation of the cockpit and cabin crew safety equipment, the particular interior configuration of the cabin, which is usually different for different airlines even using the same make and model of airliner, and with the location and configuration of the emergency exits. An exact knowledge of the size, contour, and color of the objects that the pilot's body may have hit is extremely helpful in evaluating the injuries observed in and on the body. The pathologist should confer with pilots, engineers, and other experts who are familiar with the aircraft, parachute, ejection mechanism, and other equipment, to gain first-hand knowledge.

The second step in the investigation is for the pathologist to acquaint himself or herself with all available information relative to the flight: the nature of the accident, severity of damage at the crash site, known factors about the weather, airfield, the health record and past performance of the pilot and his or her condition before and during flight, information regarding the passengers, the nature of any radio contact, and other pertinent information. Similarly, the same factors for the flight attendants must be gathered for analysis later.

The third step in the pathologist's investigation consists of careful observation and written and photographic records of the position of the body and its relation to the total wreckage (or the parachute and other escape mechanism), and the conditions under which the body was found. The pathologist should examine carefully the pilot's protective helmet, clothing, shoes, and any other attachments. For flight attendants, the duty locations and seats should be examined with respect to their failure modes. Regarding passengers, examiners should look for extremity fractures that could correlate with seat failures or overhead bin collapse, as well as evidence of inhalational toxins. Examiners should compare where passengers were assigned seats, or actually sat, and their final resting location within the fuselage or outside the aircraft. Using representative yet simple diagrams and simple color-coding schemes, one can store a multitude of details regarding the postcrash events in the field phase of the investigation. In Figures 25-10 and 25-11 some of the survival factors information is encoded visually. In the absence of the pathologist on the crash scene, these items should be left on the body as recovered. No article of clothing, harness, and

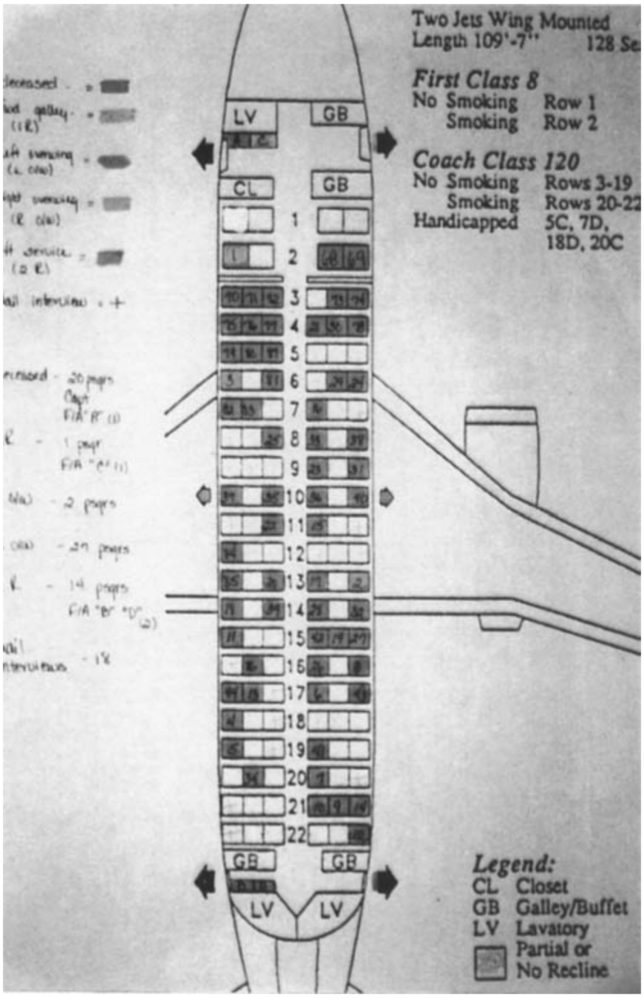


FIGURE 25-10 Typical on-scene working document for aircraft occupant egress, injury, and death information as part of the field notes of the Survival Factors Group (photo courtesy of Civil Aerospace Medical Institute).

so on should be cut or removed before inspection by the pathologist. The protective helmet and articles of clothing, shoes, gloves, and so forth, may reveal important information about the crash and may suggest defects in the design of the plane. The soles of the shoes or boots may contain a reversed imprint from the rudder pedals of whatever logo or pattern is on the rudder pedal surface. Cytologic and ultraviolet light studies may offer helpful data.

The fourth step performed by the pathologist and his assistants will consist of meticulous examination of the exterior of the body and the viscera, with necessary close-up photographs and radiographs, and removal of properly selected tissue for chemical, toxicologic, and histopathologic examination. Special attention must be directed to the detailed examination of all abrasions, lacerations, and superficial and deep wounds. For example, a single small wound on the lateral or posterior portion of the lower legs may be strong evidence that ejection occurred but that the individual's feet were not positioned properly at the time. Photographing such wounds will be of great assistance in later correlation of the findings. Specimens of urine, blood, liver, kidney, and brain (unfixed) are necessary for toxicologic analysis for over-the-counter, prescription, or illegal medications and drugs. In recent years, alternative medicine compounds have arisen as another factor to be examined in postmortem testing. For histopathologic examination, tissue sections from all organs—including the skin, bone, middle and inner ears, entire brain, spinal cord, entire heart and aorta, and organs showing significant lesions—should be preserved in 10% neutral formalin. These sections should include not only the diseased or traumatized area of the organ, but also its margin and the adjacent normal area. In cases where a less than complete body is recovered, the examination of the remains should be conducted as conditions permit. It is essential to find as much of the body and internal organs as possible. The condition of the heart, brain, spinal cord, larynx, liver, skeletal muscle, and bone may well explain the cause of the crash.

The fifth stage in the investigation consists of microscopic study of the sections and chemical analysis for poisons. The pathologist must take special notice of the occurrence of vital processes such as vascular dilatation and the cellular exudation of early inflammation in the proximity of burns, contusions, and so forth.

Summarizing the report of the accident and correlating it with the findings of the autopsy complete the final step in the investigation. On scene the factual findings will be captured in a group collection of field notes (human performance, survival factors, etc.), which will be coalesced into group factual reports as further information is collected after the on-scene phase. Eventually the investigating authority will publish a common final report with the facts, findings, probable causes, conclusions, and safety recommendations. The pathologist may participate in the proceedings of the investigating board (24).

Preliminary Evaluation

Preliminary evaluation of the crash site, nature of the casualties, available resources, and the chain of events that immediately preceded the crash will save time in the end and will allow the investigator to determine the most efficient course to follow. This early phase, which is easily underemphasized, is certainly the most important. Much of the data in the early phase of the investigation is perishable evidence, and with so many activities going on in parallel, it is often difficult to be present at all the important aspects of the investigation.

The investigator must become familiar with the type of aircraft, seating arrangement, restraint systems, structural arrangement, and emergency, evacuation, and personal equipment. He or she should examine an intact aircraft of the same type (sister ship) to become familiar with the emergency exits and equipment. If possible, this aircraft should be available for comparisons during examination of the wreckage. The sister ship and the wreckage should be photographed for comparison. A camera used along with a portable global positioning system (GPS) and a small tape

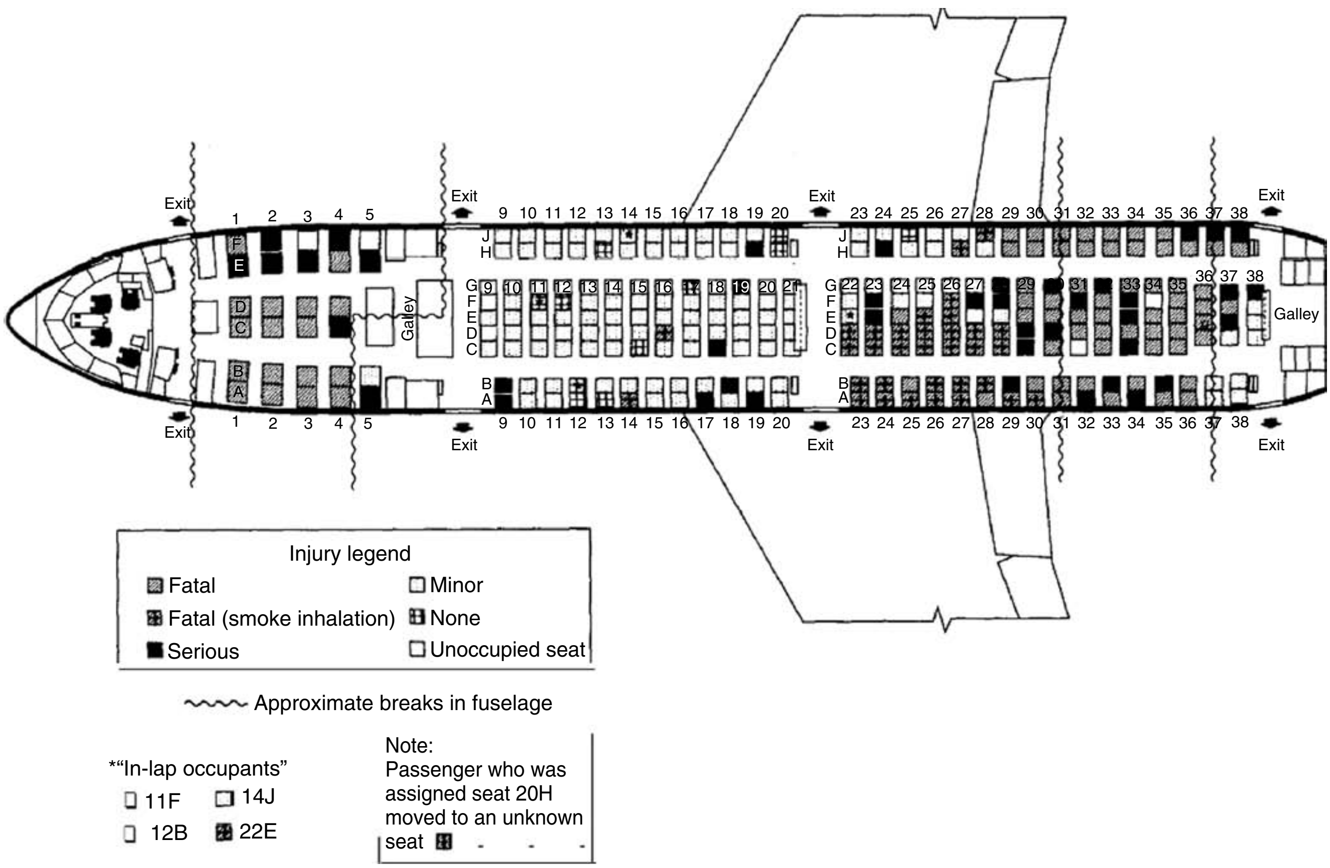


FIGURE 25-11 Typical Survival Factors summary document for aircraft occupant egress, injury, and death information for a Factual Report. (Data from NTSB Sioux City accident July 1989.)

recorder may facilitate the documentation of the location of key pieces of the wreckage for the medical investigator. The structures group is often responsible for the documentation of the wreckage, but the medical investigator may require some additional details in addition to their effort.

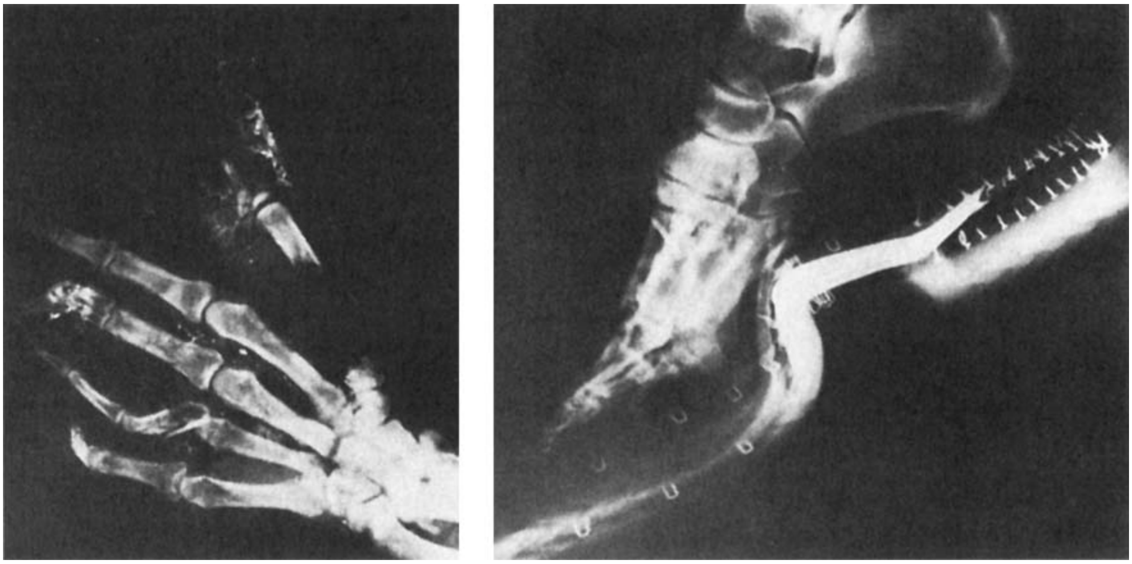
Examining the cockpit of a similar aircraft may provide important clues to correlate injuries to the pilots with cockpit structures. Comparison of details of the paint scheme of the crashed aircraft with the location of paint fragments found at the crash site may help in determining the kinematics of the occupant in the crash. Review of manuals for the operation of the aircraft and its systems, and for information about the injury patterns and accident circumstances associated with previous crashes of the same or similar types of aircraft may also be helpful.

Data Collection

The initial phases of accident investigation involve gathering information about the circumstance of the accident and the casualties. The investigator begins collecting data to evaluate many factors; background information about the general health, emotional attitude, experience level, and training of the crew is particularly important. The investigator should look for behavior patterns that might have led to errors of judgment or errors of action or reaction on the part of crewmembers, as well as for the presence of adverse physiologic conditions that might have impaired the crew. The investigator should seek clues regarding the speed, direction, and attitude of impact, which will be helpful later in analyzing injury patterns and calculating crash force vectors.

The investigator must be particularly alert in obtaining all available information about the circumstances of the accident and must coordinate this information with other groups involved in the investigation. The investigator should interview any witness because his or her observations may give clues about what occurred immediately before the crash. Even seemingly insignificant factors can be valuable to the human factors investigator in understanding the kinematics of the crash and in evaluating the causes of any unusual injuries. For example, severe turbulence associated with thunderstorms may explain the wreckage distribution after in-flight breakup.

Security at the crash site is important to ensure that no one alters the wreckage and its valuable clues as to the cause of the crash. Taking photographs and making diagrams is essential before anyone disturbs the wreckage. Well-meaning investigators often create problems by unintentionally altering crash sites. Nothing should be disturbed, after the initial crash fire rescue effort, until someone photographs or otherwise documents the site. This, of course, assumes that survivors have already been evacuated from the site.



A B

FIGURE 25-12 Radiograph of a hand (**A**) and foot (**B**) indicate that these were the extremities of the pilot, who was at the controls when this accident occurred (photo courtesy of Armed Forces Institute of Pathology).

Preaccident training and briefings for crash fire rescue personnel can help them to both reach the survivors and minimize the destruction of evidence. As an example, the rapid use of large vehicles along the impact path of the aircraft to reach the final resting place of the fuselage may obliterate important information related to the cause of the accident. Approaching in a parallel or orthogonal manner may better preserve the wreckage. Also tall vegetation (such as the corn stalks adjacent to the airport at Sioux City, Iowa, in the fatal DC-10 accident in 1989) may make the survivors difficult to locate, especially if injured and lying on the ground. Most jurisdictions treat the accident scene as a crime scene until the NTSB team arrives to take charge of the investigation. Often law enforcement officers, the military or private security forces may be necessary to secure the scene. Adequate investigation requires careful documentation of the scene, and all participants in the investigation need to consider the final location of the debris. The investigator should note the exact location of various parts of the wreckage, the location and configuration of ground impact, the stopping distance of the aircraft, and the exact amount of crush of the aircraft structure, and also record this information on a scaled diagram. The diagram should also note the location of the bodies. These notes will be helpful in the identification of bodies, estimation of crash forces, and determination of the sequence of events.

A thorough description of the nature and extent of each injury is also helpful, and photographs, radiographs, and diagrams are useful in documenting injuries. Careful examination to document preexisting disease and toxicologic studies to evaluate possible toxic substances or self-medication are also important.

Radiologic examination of the entire body, particularly the hands, feet, and vertebrae, is important. Radiographs often enable the investigator to determine who was operating the vehicle controls at the time of the crash or estimate the magnitude and direction of impact, although the control pattern fractures, such as fracture dislocation of the thumbs and ankles, may only be meaningful if present. The absence of such fractures does not impart much useful information (Figure 25-12).

A complete autopsy examination of all fatalities is essential. Autopsies of fatally injured crewmembers may uncover preexisting disease, incapacitation, medication usage, or the presence of toxic substances in aircraft, such as carbon monoxide gas. Autopsies of the passengers may speed their identification and allow correlation of the design features of the aircraft or peculiarities of the accident that are responsible for the deaths of some passengers and the survival of others.

Data Analysis

In the section Identification Techniques, we will introduce data analysis tools for the identification of mass fatality occurrences.

The investigator must diligently collect and evaluate the data. Having collected the facts, he or she must then carefully analyze the questions to be answered. Given properly posed questions and adequate investigation, most answers follow surprisingly easily. Although initial impressions as to the cause of an accident may be tempting conclusions, the investigator must not summarily dismiss any observation as insignificant. The investigator must remain unbiased while conducting the investigation and be continually aware of possible new areas in which to pursue the investigation before forming conclusions. Each piece of factual information must be weighed as to its validity. The investigator must even suspect the witnesses' observations if they cannot be substantiated with factual information. Proper evaluation of the factual data that have been collected involves ruling out all other possible explanations.

To assist in analysis of the many human performance factors discovered in the on-scene phase of the investigation, a tool has been developed for use by investigators. The Human Factors Analysis and Classification System (HFACS) is a general human error framework originally developed and tested within the U.S. military as a tool for investigating and analyzing the human causes of aviation accidents. On the basis of Reason's (1990) model of latent and active failures, HFACS addresses human error at all levels of the system, including the condition of aircrew and organizational factors. The HFACS framework as an error analysis and classification tool outside the military has been examined and has been successfully applied to commercial aviation, where it was demonstrated that HFACS reliably accommodated all human causal factors associated with the commercial accidents examined from NTSB records. Versions of HFACS are being, or have been developed, for use in general aviation and air traffic controller research and investigations (25).

Data Management Tools

In 1986, the Transportation Safety Board (TSB) of Canada developed the Recovery, Analysis, and Presentation System that used FDR information to enable recreation and visualization of the mishap events. Subsequently, the software has been adopted by many other investigation authorities.

The investigation by the TSB of Canada of the crash of an Swiss Air Flight 111 MD-11 in the Atlantic Ocean in 1998, with the loss of all on board, due to an in-flight fire (Report Number: A98H0003) was facilitated by a document management system that allowed the enormous amount of information from all aspects of the investigation to be collected, managed, and viewed in a system called *Prodocs*. Witness viewpoints, overlaid on a graphical information system of maps or grids, allowed rapid interpretation of field of view, proximity to flight path, and ear or eyewitness statements. Panoramic images of the flight deck and use of virtual reality enabled very complex sets of investigation findings to be visualized and more easily examined by groups of investigators. Using Computer-Aided Design (CAD) system, the recovery of aircraft components, their degree of heat stress or smoke damage could be documented and compared with live in-flight test findings as part of the investigation. As the highly disintegrated human remains were collected, the use of 3-D CAD layouts of the interior of the MD-11 replaced the wall-covering charts and tables that were the prior hallmark of the organization of the medical examiner results of large mass fatality events. At any given time in the investigation, one could know any of a myriad of details such as next of kin notification, which anatomic areas had human remains, toxicology results, and access thousands of photographs of relevant investigation matters.

Another visualization tool, also developed by the Engineering Branch at TSB Canada, as a follow on to the Prodocs system to assist in the collection, management, and analysis of information is the Accident Investigation Geographic Information System (AIGIS).

The increase in the amount and detail of information collected in aviation investigations has resulted in the need for an accident investigation tool that can be used in the collection, storage, retrieval, analysis, and display of spatially referenced data. Experience in the field, and research, led the TSB of Canada to improve on Geographic Information System (GIS). Because an appropriate commercial-off-the-shelf tool could not be found, it was decided to develop a prototype AIGIS. The AIGIS tool would be similar to conventional GIS in that it would allow the mapping of spatial relationships. In addition, it must also be capable of collecting, analyzing, and displaying data associated with both pre- and postoccurrence structures. These would include vehicles, buildings, and human anatomy. The AIGIS prototype is divided into two primary components, a relational database data store, and a two-dimensional (2-D)/3-D CAD application. The relational database that was selected was MS Access. The CAD application that was chosen was Bentley Microstation. It was chosen because of its availability, because it is GIS capable, and because it can be manipulated by an external program (e.g., MS Access). In order to make AIGIS a multiuser application, the database and user interface would be separated into two MS Access applications. One, the "back-end," would host the relational tables and the collected data and the other, the "front-end" would host the user interface. This separation will allow multiple users, each possessing their own copy of the front-end, to access a shared back-end.

The developmental aspect of the AIGIS framework consists of data table and user form templates from which new tables and user forms can be rapidly developed and deployed. These templates have reusable custom code associated with them which, among other things, facilitates data entry, data querying, and data display. Consequently, AIGIS can be quickly deployed, and new tables and forms can be rapidly added, removed, or modified to adapt to new circumstances and rapidly changing priorities. Because the database (MS Access) and CAD (Microstation) applications are separate programs, they can function independently of one another. However, the true power of any GIS is its ability to graphically display spatially referenced data. Consequently, the AIGIS framework includes custom code that facilitates two-way communications between MS Access and Bentley Microstation. This means that, through the framework, MS Access can send information and commands to Microstation causing it to selectively and systematically generate 2-D and 3-D plots depicting things such as occurrence site maps and pre- and postcrash structures (e.g., vehicles, buildings, and human anatomy). Questions of the data store are based on Structured Query Language (SQL) queries that can be based on any available field or combination of available fields, and can be easily created by filling in the same forms that are used for data entry. The results of these queries are automatically displayed back into the master and its subforms. The user interface framework also allows queries to be modified, saved, and restored. The user interface framework also simplifies CAD plotting. Plots can be systematically built up, saved, and restored. They can be created in steps, each step representing the results of a database query. These steps can be saved and later recalled to either recreate the plot or to be used as the foundation of additional plots.

The AIGIS foundation software has been used to create two variations of AIGIS. They are AIGIS Wreckage and AIGIS Pathology. As the names imply, AIGIS Wreckage is used to collect, store, retrieve, analyze, and display data associated with vehicle wreckage components, and AIGIS Pathology is used to collect, store, retrieve, analyze injury data associated with the accident occupants. Both variations have some common tables and forms. For example, each has ‘‘Photo’’ tables and forms that host the photographs associated with the wreckage component or occupant. Among other information a ‘‘thumbnail’’ of each image is shown, which, when selected, will launch a high-resolution version of the image located in near line storage such as optical storage devices, servers, or other network attached storage devices.

AIGIS Wreckage was adapted to include tables to host among other things pre- and postcrash component descriptions, locations (i.e., where the component was located in the precrash vehicle and where it was found in the wreckage field), and multimedia data (e.g., object models, panoramic images, video, and audio). For one specific investigation, this variation of AIGIS was used to host and analyze more than 20,000 exhibits, more than 160,000 images and was used to track and plot more than 35,000 CAD graphic objects.

AIGIS Pathology was also adapted to host occupant data, which, among other things, included demographic information, next of kin, personal effects, exhibits (i.e., body parts), injury, and toxicology. In addition, a special plotting utility was added that allowed 3-D avatars (computer virtual mannequins) to be placed in a CAD model depicting the interior of a vehicle (i.e., a mannequin for each victim). These mannequins, one male and one female, were scaled to indicate whether they were an infant, a child, or an adult. Each mannequin was divided into 16 segments (i.e., left and right aspects of the head, face, neck, chest, arms, abdomen, pelvis, and legs) and each segment was linked to the database allowing manipulation of the individual segments, and allowing the database to be queried from the CAD application. In addition, human anatomic CAD models were added which would allow a detailed analysis of an individual's injuries. The AIGIS Pathology portion can be used to great advantage in a wide range of diverse uses. The list of such uses includes but is not limited to, victim recovery and identification, selecting of victims for toxicology purposes, and the analysis of injury patterns. In one occurrence, the system was used to collect, track, and analyze data for 229 fatalities. During one 4-hour session, approximately 80 different questions (e.g., where were the people with tibia or fibula fractures seated?) were answered. This included the creation of approximately 80 different 3-D mannequin seating plan plots, one for each question asked. Figure 25-13 shows a CAD display of assigned seating information from two air carrier fatal accidents *DCA89MA063* and *DCA99MA060*. The gray shading is only meant to be illustrative of what is possible and is, in this case, random shading.

AIGIS has proved to be a very powerful tool and the prototype has exceeded expectations. However, there are areas that need improvement and additional features that should be added. Growth of data sets can be so rapid as to exceed the functional limitations of the MS Access software and a multiuser environment can slow the system considerably. Relational databases such as SQL Server, Oracle, or open source platforms such as MySQL and others could be considered for future development efforts of AIGIS. The AIGIS prototype is limited in that it can only deal with one occurrence at a time. An ability to query across multiple disaster occurrences would be beneficial. Both AIGIS Wreckage and AIGIS Pathology need to be combined into one product. This would allow a better analysis of the human–machine environment. AIGIS should also be expanded to include statistical analysis and charting modules. Using a data store such as SQL Server or other commercially available software will also allow sophisticated data mining products and statistical packages direct access to the data store using native drivers, and SQL in addition to ODBC access. The TSB of Canada uses animations of the recreations of the sequence of events in aviation, rail, and marine accident investigations.

Conclusions

After determining and evaluating the facts, the investigator must reach conclusions as to the cause both of the accident and of the injuries received by the passengers and crew. Three of five important questions that Fryer proposed must be answered in the conclusion and recommendation phases (26):

1. Why did the fatally injured lose their lives?
2. To what feature of the accident or of the aircraft can the escape of the survivors be attributed?
3. Is there any indication that the main cause or any subsidiary causes of the accident might have been of a medical nature?

The conclusions should reflect the investigator's best opinions based on the available factual information and should include comparison with the existing literature and previous similar cases. The sequence of events and the chain of circumstances that led to the accident or to the specific injuries need to be documented in as much detail as possible during the investigation. This may include more detail than the investigating authorities may need to develop their probable causes under the specific legal mandate they have to do the investigations. However, the medical report should contain such additional data to permit later research of the findings of many accidents over a period of years. After defining substantiating facts, reasonable speculation is

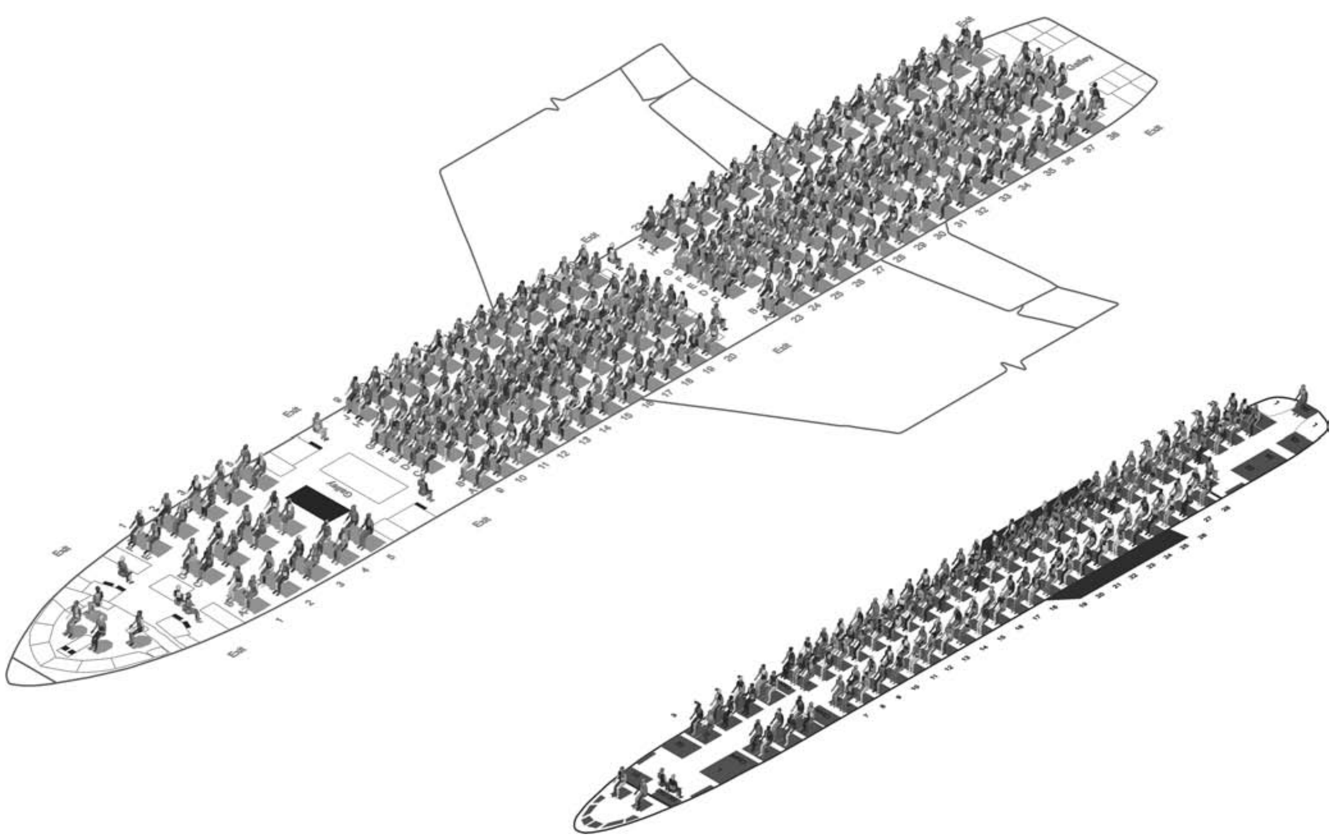


FIGURE 25-13 Accident Investigation Geographic Information System (AIGIS)-generated graphic of DC-10 and MD-80 with passenger assigned seating data from accident investigations, the anatomic coding is of random coloring for illustrative purposes only (NTSB data, photo courtesy of Transportation Safety Board of Canada).

of definite value in deriving conclusions and may serve to alert others to potential safety hazards that can be sought in other accidents. A determination of "cause: undetermined" does nothing to advance the prevention of accidents and injuries.

Recommendations

The investigation is not complete until the investigator makes recommendations for changes that will prevent similar injuries and fatalities and, if possible, prevent the recurrence of the factors that caused the accident. The recommendations should address at least Fryer's (26) last two questions:

1. Would any modification of the aircraft or of its equipment have improved the chances of survival of those killed or reduced the severity of injury of the survivors?
2. Would the incorporation of such modifications have a detrimental effect on the chances of any of the survivors?

MASS DISASTERS

Forensic Identification of Human Remains

Investigating a mass disaster is a complex task, and identifying the casualties is one aspect that can be particularly difficult if it is not approached in a scientific and systematic manner. Regardless of the nature of the disaster, be it a natural calamity, transportation-related, or other human-induced chaos, investigators participate as members of multidisciplinary teams to deal with the environmental and human aspects of the disaster, conduct an investigation to reconstruct the event, gather the facts, determine the relevant sequence of events and the chain of errors, and establish preventive measures for the future.

Many investigators know about identification techniques, but they have considered them as an isolated process and have not integrated them into the overall investigation. Typically, physicians, dentists, and other medical personnel are assigned tasks based on a preconceived disaster plan that they had no role in developing. The practical aspects of the identification process then usually develop on an *ad hoc* basis.

The identification process is an essential element of an adequate investigation. Accurate identification of all fatalities incurred in an aircraft accident or other mass disaster is often the first step in determining where each person was located at the time of the disaster and what role he or she may have played in its cause.

Another obvious reason for identification is to allow families to recover the correct body. After some disasters, inexperienced people determined identity solely based on the visual inspection of physical features, clothing, and items of personal effects such as jewelry and dog tags. They allowed families to claim portions of bodies even when no identifying characteristics were present, and when religious beliefs required prompt burial, families were often quick to claim any body. Grieving during the emotional period after the death of a family member sometimes produced denial reactions and families refused to accept definitive identification of their relative (McMeeken, *personal communication*, 1985). Although visual inspection is usually more than adequate, possible litigation or insurance claims may hinge on documenting that the victim was, in fact, correctly identified.

The successful development of DNA identification methods for tissue, mitochondria, and bone has made these methods the mainstay of the identification process. Therefore, DNA identification has greatly enhanced the ability to accurately identify individuals from even miniscule pieces of tissue. However, they have not eliminated the use of traditional identification techniques, which should be learned by accident investigators as back-up methods because DNA identification methods may not always be available or feasible, or no DNA matching tissue or records are available. Ideally, DNA from the accident victim is compared with their own DNA from hairs, toothbrushes, blood, or other sources from before the accident. When that is not available, then postmortem samples are collected and compared with DNA from living relatives, such as parents or siblings. Sometimes there will be no other DNA sources to make a comparison. It has happened that an individual cannot be compared with family members due to adoption, and occasionally it may be discovered that some or all of the surviving kin were not related by blood to the accident victim, a fact that may only be revealed as part of the mass disaster investigation and that clearly requires special sensitivity.

Identification efforts in aviation disasters with mass casualties (TWA 800, Swiss Air 111, Galaxy 2003, and others) have led to the development of software tools to assist the forensic odontologists/pathologists in their efforts. The advent of the unique problems and the volume of data that arose in the aftermath of the World Trade Center Disaster, September 11, 2001 required the development of additional bioinformatics tools, and highlighted the problems that the investigator will face in mass casualty situations with high body fragmentation. In a table of complicating circumstances the following were noted (27):

- Remains recovery is partial.
- A proportion of recovered remains has incurred significant thermal/chemical/bacterial decay.
- Many of the most probative personal effects are unavailable.
- A proportion of available personal effects recovered from the victims' residences carry biological trace material from an individual other than the anticipated victim.
- Partial or complete families may be among the victims, thereby making pedigree reconstruction from within the victim's data set necessary.
- Older victims present additional challenges to the process of reconstructing parentage diagrams using DNA typing.
- Many victims may have few next of kin who can be used as genotypic references.

The task of identifying disaster victims is not difficult if it is approached in a logical, meticulous manner. Separated into basic elements, the identification process involves (a) the collection of identifying information about the missing persons, (b) the observation of identifying features of the victims, and (c) the comparison of the two groups of information. Identification is impossible if any one of these three elements is inadequate.

Planning for the Unknown

The first phase of identification occurs or should occur long before the actual event with disaster planning. The degree to which preparations are made in advance of the investigation will largely determine the degree to which the investigation will be successful.

The following discussion of the planning process is largely theoretic, rather than a systematic description of a plan. Each community must individualize its disaster plan after full consideration of the types of disasters that may occur.

The most serious drawback of any disaster plan is that no one can determine exactly where a disaster will occur. Many airline accidents happen at airports or near airports. In 1994, during a go-around maneuver in a thunderstorm with a microburst causing wind shear, and with the crew affected by the somatogravic vestibular illusion, the aircraft failed to maintain the proper climb attitude and contacted the ground with the main landing gear on the airport property in an open field. The aircraft impacted trees and the airport perimeter fence, crossed a residential road in pieces, and part of the aircraft impacted a private residence (Figure 25-14). Although many high-risk areas can be identified, with the current modern transportation technology and ever-increasing air traffic, the possibility cannot be eliminated that an accident will occur in dense population areas, such as the El Al 747 cargo freighter impact into an apartment building near Amsterdam on October 10, 1992, which caused 47 fatalities, the loss of a 747 aircraft, and two apartment buildings (28). (http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=173116).

For this reason, planners often cannot properly select the necessary facilities until after the disaster has occurred, and the investigators know the nature and number of casualties and the location, type, and severity of the disaster. Accidents with ocean impact scenes complicate the jurisdiction and the recovery of the information to conduct the investigation, increasing its complexity and cost, and magnifying the risks to the investigating and recovery teams (Figure 25-15).

Regardless of these difficulties, predisaster planning must take place (29). Although successful investigation of disaster and identification of the victims may be possible without a plan, the job is much easier when all involved know what their role is and what they must do. Unless the planners have already considered the theoretic aspects by planning, the necessary decisions usually cannot be made rapidly and

A

B

FIGURE 25-14 Crash scene in a residential area near the perimeter of the airport at Charlotte, North Carolina (photo courtesy of NTSB/Civil Aerospace Medical Institute).

FIGURE 25-15 Swiss Air 111 investigation ocean accident scene during recovery operations (photo courtesy of Transportation Safety Board of Canada).

correctly. Expedition of the identification process after the occurrence of a disaster will more than compensate for all the time spent on predisaster planning.

Planners may be able to follow certain guidelines when developing a preaccident plan, but direct incorporation of someone else's plan is usually not possible without at least some modification to accommodate specific circumstances. The plan must reflect the risks, resources, and decision-making process unique to the community in question. A plan that could be used successfully in New York, for example, may not be suitable for a small town of 3,000 to 4,000 individuals. The larger cities have more extensive resources to purchase equipment and hire full-time staff, allowing them to respond more efficiently to a wider range of disasters. On the other hand, the larger cities have more bureaucratic channels that often make even the simplest decisions complicated. Smaller communities and medical examiners' offices should consider appealing to the governor of their state for aid to civil powers in such emergencies to allow federal and state resources to be committed to the mass disaster. Investigation team members can provide this advice to the local authorities on scene to help coordinate the process. Even in the most carefully thought-out plans, some unique circumstance may arise that the planners did not anticipate.

Nevertheless, a facility that is prepared for the eventuality of a mass disaster will be able to cope on a larger scale than will the facility that has no organization or plan. The unprepared facility must organize rapidly after a disaster occurs and is likely to make mistakes that would not have been made had more time been available for preparation.

Initiating the Planning Process

The disaster investigation organizer or committee can benefit from reviewing the plans and experiences of other communities, although the plans may not appear directly applicable. Reviewing accident reports and contacting investigation authorities for advice are logical first steps. The next step is a brainstorming session to see how many different possible disaster scenarios the planners can develop. The important questions concern (a) what types of disasters might occur, (b) where they might occur, (c) the magnitude of the risk of occurrence, (d) how many casualties might occur, and (e) what resources will be available.

Casualties

Results of an NTSB public meeting on airline survivability in February 2001 were noted in an earlier section of this chapter. In a 7-year span to the year 2000 involving serious airline accidents (those involving fire, serious injury, and either substantial aircraft damage or complete destruction), there were 2,739 occupants; 1,524 (55.6%) of those occupants survived (4). Categories of casualties consist of persons who are killed, injured, or displaced from homes. The nature and severity of the disaster influences the number of persons to be found in each of these categories. Generalizations are difficult, but Lane and Brown (30) studied this problem in relation to 1,086 aircraft accidents involving 34,369 occupants. They reported that no occupants were seriously injured in 82% of the accidents, that more than 50% of the occupants were seriously injured in less than 1% of the crashes, and that in most accidents (95%), not more than 25% of the occupants were seriously injured. Although no amount of planning can totally prepare a community, disaster drills are an effective way to test the plan before an actual disaster occurs (30). The drill may point out weaknesses in the plan; seemingly insignificant details often turn out to be critically important when the actual disaster occurs.

Preaccident planning and drills involving the airport, the National Guard, the local hospitals shortly before the accident at Sioux City in 1989 were responsible for the prompt, efficient, and comprehensive crash fire rescue response that was mounted in the minutes after the crash. Certified airports are required to have live drills every 3 years with paper exercises in the interim years. Sioux Gateway Airport is not certified for wide-bodied aircraft, their prior accident drill involved a bus. In 1989 the city disaster coordinator decided on a disaster preparation live drill for the Sioux City airport with a simulated mishap involving a wide-body aircraft crashing on an unused runway, with 150 survivors. Aircraft rescue and firefighting (ARFF) services were provided by the Iowa Air National Guard 185th Tactical Fighter Group. The planners learnt from this drill that their plan needed some improvements and flexibility, most or all of which were in place when the crippled DC-10-10 with 285 passengers and 11 crewmembers crashed on the runway. There were 175 passenger and 10 crew survivors and this survival proportion could be attributed to the presence of 285 National Guardsmen (now the185th Air Refueling Wing) based at the airport and trained in the airport drill, the professionalism of ATC, the readiness of the emergency medical service (EMS) ambulances, the hospitals, and the surrounding communities (Captain Al Haynes, *personal communication*, 1998). An article in the journal of *Organization & Environment* published in 1991 also reviews the circumstances of the Sioux City disaster planning (31).

Security and Access Control

Security procedures to protect the disaster site are important. Looters can quickly strip all identifying evidence from the scene, and bodies and baggage are inviting targets. Some disruption of the site may be inevitable in the course of rescuing survivors, but beyond this initial stage, strict security measures should allow only trained investigators or other specially instructed personnel to enter the site. Disruption of the disaster site compounds an already difficult identification task, and uncontrolled access to the disaster site or to the investigation facilities can have disastrous effects on the outcome of the investigation and the safety of the investigators. Likewise, appropriate security measures must be taken at the investigative facility to prevent unauthorized entry. Suitable isolation may be necessary for family, news media, and other persons who have a legitimate interest in the investigation but whose presence may distract investigators and result in errors of identification. This consideration usually dictates selection of a site for the identification facility somewhere other than a centrally located public place.

Blood-Borne Pathogen Protection

Controlled access also provides a means of providing blood-borne pathogen protective measures. Universal precautions, such as the use of masks, gowns, and gloves, go a long way in providing protection to persons requiring access to the crash scene. Securing the scene and controlling access to contaminated wreckage minimizes the chance of injury or infection arising from contact with human remains. At the limited number of entry control points, changing stations should be provided with supplies of gowns, gloves, and footwear coverings. These entry and exit points will also need rinsing and decontamination stations and a log of access to the scene. Documentation of injured investigators must be maintained as part of their separate medical record. Although there are no cases on record of hepatitis B virus or human immunodeficiency virus transmission from an accident scene, there have been other occupational injuries and illnesses, including death of a toddler due to organophosphate chemicals from the accident scene being transposed to the home by boots worn on the contaminated accident scene (Véronneau, 1990). The toddler crawled across the chemical traces on the carpet at home and died as a result of organophosphate insecticide poisoning.

Jurisdiction over Human Remains

The investigator should determine the legal aspects of jurisdiction to proceed with the investigation because many people have legitimate interests in actively participating in the investigation. Rescue teams are concerned with saving the lives of those who have been injured, and these efforts necessarily take precedence over other investigations. The fire department responds to extinguish the fire and investigate its cause. The police investigate possible wrongdoing, provide security, and control spectators. Many police, fire, and rescue teams may respond, and the question of who has primary jurisdiction may not be clear.

The medicolegal jurisdiction in which an aircraft mishap occurs is responsible for the identification of fatalities in the aircraft mishap. The laws of that jurisdiction drive forensic procedures. Within the United States, a jurisdiction can be exclusive or concurrent. It can be federal, state, county, or local. Federal regulations direct medicolegal postmortem examinations on aircrew members. State and local requirements on nonaircrew fatalities may vary. Deaths of U.S. citizens overseas fall under the jurisdiction of that international government and the United States Department of State. The Armed Forces Medical Examiner's staff has routinely accomplished identification of many such fatalities. Status of Forces agreements between countries define how deceased military members will be managed.

Medical Examiner, Coroner, and Justice of the Peace Systems

A wide variety of systems for death investigation and identification exist in the United States. They range from a statewide medical examiners system, regional medical examiners within states, county or metropolitan area medical examiners systems, and coroner systems to justice of the peace systems. Combinations of these systems exist in many states. Some officials are appointed and some are elected. Education, skill, and experience vary widely. Facilities, staffing, equipment, and support capabilities also vary. One important task after an aircraft mishap occurs is to determine the forensic capabilities of the jurisdiction where the mishap occurred. A second task is to gain the needed professional support to augment that system. DMORTs, the Armed Forces Medical Examiner, and the Armed Forces DNA Laboratory may be of assistance if state agencies are unable to provide the support. The FBI Disaster Fingerprint Team is always available on request and at no cost to the local jurisdiction. Since TWA 800, the federal NTSB Family Assistance Center is available to support families of fatalities and the local forensic identification center when aircraft mishaps occur. Their ability to locate antemortem records and radiographs is noteworthy. The law pertaining to the Family Assistance Center has been modified to support most transportation mishaps. However, no other type of disaster is covered. State governors may request active duty military support under Public Law 93-288 when state agencies lack the capabilities needed. Most major aircraft mishaps are treated as a crime scene until proved otherwise. Consequently, federal, state, county, and local law enforcement agencies may be players on the scene. FAA teams, NTSB teams, FBI teams, airline representatives, and the aircraft manufacturer are also involved. Some states already have well-experienced identification teams. States are now required to have disaster plans.

Medical examiners and coroners take leadership and examine the bodies to document the cause of death, detect possible infectious disease, and assist the police in detecting evidence of foul play. Representatives of the news media have a role in reporting the circumstances of the event and communicating the extent of any continuing hazards to the community. Undertakers want to prepare the bodies as quickly as possible. The operator of the vehicle or industry involved in the disaster is interested in determining the cause, and relatives want to ascertain the status of missing family members. The unions for the pilots, flight attendants, mechanics, and air traffic controllers will also want to be present. Attorneys have an interest with the potential plaintiffs and defendants to determine their possible claims and liabilities. In the case of transportation disasters, representatives of various agencies such as the NTSB and the FAA also participate. The international nature of many disasters poses special problems for international relations.

These are only a few of the individuals and organizations that may have an active interest in the investigation, and the process must provide a framework for all interested parties to work together.

Leadership

Lack of consensus among the early arrivals as to who should be in charge is one of the greatest problems at the scene of a mass disaster, especially when not all of the investigators were participants in a preconceived plan. Many interdependent decisions are made, and too many people attempting to assert command and give orders only increases the state of mass confusion.

The NTSB is the statutory authority for the conduct of the investigation and the determination of the cause of the accident, and the local medical examiner or coroner is the authority for determination of the cause of death. The NTSB's investigator in charge works with local, state, and other federal agencies to ensure that the accident site is secured, safe, and ready for their investigators to proceed. At the end of the investigation, the scene will have to be handled by local authorities as part of a cleanup effort to restore the area. Although each of the activities will have a leader, the various parties with interests must acknowledge that the NTSB will have primary control of the overall investigation. Until the NTSB arrives, the logical controlling authority would be local law enforcement officials, who should treat the accident scene as a potential crime scene.

Medical Investigation Headquarters Site

The medical investigator must establish a local central headquarters to control and monitor progress in the investigation and to maintain necessary liaison. This headquarters must be easily accessible to transportation and communication, although it need not actually be within the identification facility. In many respects, investigators find it advantageous if the headquarters is separate from the identification facility when it comes to dealing with the press, families, and others whose presence may disrupt the identification process. Accommodations for eating and sleeping may be necessary.

Disaster Identification Facility

The aircraft disaster identification center should operate in a preestablished location when possible under the leadership of an accomplished and experienced chief in accordance with a disaster plan that has been exercised and updated (32). The ID center should include the following sections: ID Center Chief, Public Affairs, Communications, Security and Support, Fingerprints, Pathology and Laboratory, Forensic Dentistry, Anthropology, Radiology, Photography, Personal Effects, Registrar and Computer Systems, and Family Assistance Center (33,34). Most aircraft mishaps present closed populations for identification. However, when ground fatalities are associated with the mishap, the population for identification becomes open. When dealing with an open population, the jurisdiction must have a system for the reporting of missing persons potentially connected with the mishap.

As the investigators begin the process of finding a site to set up an identification facility, a number of considerations should come to mind. The facility should be convenient to the disaster site, and the problem of removing casualties should not be complicated by moves of great distances. The investigators will need to make repeated trips from the facility to the disaster site, and these trips may waste time unnecessarily if distances are too great or the terrain is too difficult.

The facility must have adequate equipment or at least be located such that needed equipment can be installed quickly. Commercial power lines or portable or mobile electrical generators can provide adequate electricity to power lights and electrical equipment. Refrigeration may be needed to protect temperature-sensitive reagents and foods, and large refrigerated storage vans may be required to store the bodies before identification and release to next of kin. Work gloves, rubber gloves, pencils, clipboards, waterproof tags, plastic bags, sawhorses, and plywood to construct examination tables, and heavy-duty plastic sheets to cover floors may be needed. Temporary autopsy rooms can be constructed in aircraft hangars or other suitable buildings to handle large numbers of fatalities with decorum and security as was done during the Swiss Air 111 accident investigation (Figure 25-16).

Although there are many reasons for conducting the identification process as near the disaster site as possible, other factors may override this plan. For example, the availability of refrigeration, communication systems, and other facilities are important factors the investigator must consider. The problem of working in a hostile environment must also be taken into account. If computer equipment is used it must be of the "ruggedized" variety else it will be of use only where there are adequate facilities for charging and where the ambient environment can be kept within their operating characteristics. Laptops do poorly in hot humid conditions.

Given a choice, most investigators opt to set up operations in a well-equipped headquarters that is selected, operated, and equipped exclusively for disaster investigations. Unfortunately, the location of disasters often cannot be

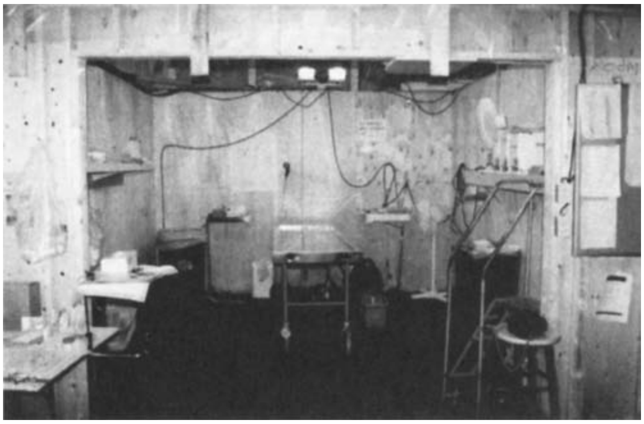


FIGURE 25-16 One of several temporary autopsy rooms set up inside an aircraft hanger, which served as the morgue for the Swiss Air 111 investigation (photo courtesy of Civil Aerospace Medical Institute).

foretold. Most communities cannot afford the luxury of a specially designated disaster headquarters and necessary associated facilities, and the number of fatalities in a disaster may far exceed the capacity of established morgue facilities. Frequently the disaster investigation facility has to be created after the disaster has occurred.

Communications

The establishment of an effective communications system should have high priority. Communications are also the priority of the rest of the investigating groups, and the medical investigator is usually provided with access to the communications setup for the investigation as a whole. The investigator must seek information from outside sources to correlate with identifying characteristics, and obtaining antemortem records and other information for use in identification may be impossible without adequate means of communication. The coordination of operations at the disaster site, hospitals, mortuary, headquarters, and other facilities also requires communications. Telephones and cellular telephones are usually the most needed means, but radio communications may also be needed, especially to the disaster site. Security of information is a concern, particularly with cellular telephones, although digital cellular telephones offer better protection against eavesdropping.

The investigator must consider public relations. Often the success of a disaster investigation depends on public support. The assistance of the local community can be invaluable, particularly by providing lodging and mess accommodations, canteen facilities at the disaster site and headquarters, transportation, communications (radio, telephone, and runners), secretarial and clerical help, and general construction help and labor. The dissemination of adequate information requires attention to ensure that the public is aware of the continuing activities and of any needs for local participation. On the other hand, apart from problems of security, continuous and uncontrolled access to the facility by sightseers is not desirable.

To provide reasonable access for press representatives, who invariably have an interest in the causes and effects of the disaster, as well as the conduct of the investigation, the medical investigator should coordinate with the investigator in charge to handle public relations.

Transportation

The investigator must consider transportation requirements. Injured persons need transportation to medical treatment facilities; bodies must be removed to a mortuary; personnel must be transported to and from the disaster site, mess facilities, and sleeping accommodations; equipment must be brought to the facility for installation; mail and other documents to aid in identification and treatment must be transported; and special requirements may exist for transportation of materials to specialized laboratories for analysis.

Personnel

Typically, communities are entirely unprepared for a disaster. Implementation of a previously designed plan can be the most important step taken when a disaster occurs. Even if the community has elaborate predisaster plans, people will not be sitting in well-organized disaster centers with all of the necessary equipment, poised and ready to go. Therefore, a critical element of any predisaster plan is notifying participants and giving them instructions as to what they must do.

The investigator must determine what personnel will be needed to cope with the emergency and often must select appropriate personnel, equipment, and a work site on short notice and without direct knowledge of the nature and scope of the disaster. Extra attention at this point invariably simplifies subsequent tasks.

Fortunately, finding people who are willing to assist in the investigation is seldom a problem. Most people in a community respond in any way they can. The more serious problem is finding sufficient professional staff in large-scale disasters.

Care and Feeding

Logistic problems must be solved if food is to be brought into the facility; likewise, transportation requirements are involved if the workers must leave the facility to find mess and sleeping accommodations. The facility should be selected with consideration for the comfort of the workers who will be using the facility. One cannot expect workers to function effectively under extremes of temperature or humidity. Adequate heat and ventilation must be provided, and mess and sleeping facilities may be required. The conditions under which the investigators must work often influence the speed with which the problems can be resolved. The establishment of work schedules is necessary, especially in adverse climatic conditions. Errors made as a result of fatigue, hypoglycemia, or cold can delay the investigation far more than any possible time saving from extended hours of work under adverse conditions. Investigators should realize that from the commencement of the investigation, long hours of duty along with difficulties in getting quality sleep will lead to the accumulation of hours of sleep deficit and that the investigation team will start to encounter fatigue-related problems even after as little as 2 long days on scene. For example it is not uncommon to have an 18-hour or longer period of activity on the first day of investigation, after traveling to the accident site, with similar long days to follow. Keep aware of the need for personal safety and watch for and prevent fatigue-related errors in the data collection and occupational accidents happening to the workers in the first week.

Viewing large numbers of casualties imposes tremendous psychological stress on all members of the team. Nightmares and altered personal behavior patterns, such as drinking and engaging in hazardous activities, represent potential individual responses that carefully organized psychological support can often prevent. In practice, most disaster workers consider religious leaders, such as priests, rabbis, and ministers, less threatening than psychologists and psychiatrists. A major key to successful psychological support in these situations is allowing the workers to express their anxiety and reassuring them that their feelings are normal. The Red Cross is often involved post accident to assist with potential posttraumatic stress disorder, which may be occurring in the survivors, the next of kin, the witnesses, and investigators of accidents.

Inventory Control

A key factor in disaster victim identification is inventory control. This includes tracking people as well as items of interest to the investigation. A medical inventory system will greatly facilitate keeping track of each fatality and survivor. This control must begin with the first rescuer on the scene. Law enforcement officers have training in chain-of-custody control and can provide a much-needed orderly handling of accident materials, including logging and tracking systems. Even if the accident does not contain elements of criminal activity, the law enforcement model and participation of law enforcement officers are beneficial to the investigative process.

The problem of inventory control may be attacked in a number of ways. One method is to establish an inventory control subgroup. The most effective method involves locating this subgroup at the disaster site, triage area, morgue, hospitals, holding area, and central command post. The duties of the inventory control subgroup are to see that all casualties were properly and securely tagged and not commingled. Furthermore, they should keep a running inventory of exactly where each survivor is located, as well as the current stage of the identification process of each fatality. The ID center normally will develop a processing line for examining the remains. The following line has proved highly successful in many disasters: (a) in processing, (b) photography, (c) personal effects, (d) fingerprints, (e) radiology, (f) forensic dentistry, (g) pathology and laboratory, (h) mortuary affairs, and storage and shipping (Morlang, *personal communication,* 2007). The ID center will only be as successful as the recovery team at the mishap site. Support and train them well.

Rescuers should remove only survivors unless immediate danger threatens further destruction and loss of the identifying features of the fatalities. When survivors are removed, they should be questioned to determine their names and other identifying information in anticipation of the possibility that their conditions may suddenly deteriorate *en route* to the treatment or holding facility. This questioning is particularly important to avert the situation that occurs in large-scale disasters in which a complete list of missing persons is frequently unavailable, thereby rendering the identification of fatalities more difficult. GPS-capable equipment can record, with the touch of a button, the location of people or items at the crash scene. This may be of benefit for both the deceased as well as the survivors to not overly rely on memories of survivors and/rescue personnel as to where everything was when questioned later in the investigation. It may be the only existing position information if the accident scene is destroyed or substantially altered by events beyond the control of the investigation authorities.

All survivors are taken to the initial triage area, usually a medical facility, so they can be queried more completely as to their identity. After referral to a holding area, investigators can question uninjured survivors as soon as possible, to record their observations during the accident. Persons who are displaced from their homes must be accommodated in this area until other arrangements can be made, whereas others may be returned to their homes. Injured survivors may be transferred to the holding area from the hospital after they have been treated.

Injured survivors, depending on the severity of injuries, should be transferred rapidly to a medical treatment facility. Care must be taken to ensure that haste does not interfere with inventory control. When more than one medical treatment facility is being used, it is not difficult to "lose" casualties. Investigators must know who is where. Casualties who die *en route* to or at the medical treatment facility must be transferred to the mortuary facility. Errors in accounting for the deceased have led to bodies being inadvertently left in wreckage and subsequently being discovered later during the investigation or wreckage movement efforts.

Much more care is necessary in the recovery of fatalities to preserve identification information. Valuable information that would be helpful in identification is often lost when recovery is unplanned and hastily performed. The exact location where the fatality was found must be recorded. In the case of mass disasters such as aircraft accidents, this record can conveniently take the form of a wreckage diagram indicating the recovery location of each of the bodies. This chart may provide helpful clues in the identification of family members. In the identification of crewmembers in an aircraft accident, knowing which bodies were found in the cockpit wreckage and, if possible, the description of the seats in which each body was found is helpful. Photographs should be taken of each body in place at the scene before disturbing the position of the bodies. Although these photographs are primarily of interest to those who are investigating the cause of the accident or the survivability aspects, they may also be useful in identification to detect any errors that may occur in the numbering of bodies. Obviously, for this to be valuable, the body number must be conspicuous in the photographs. These data can be entered into CAD software programs that use aircraft schematics to allow the visual representation of the various data elements as they are collected on scene. This can be a powerful immediate accounting and processing tool for the medical examiner and a very powerful 3-D graphic tool later in the analysis phase of the investigation.

Forensic Data Management

Forensic data can be maintained on forms or stored within computer systems with software such as WINID3. WINID3, a freeware program, can be downloaded from the Internet. Web-based versions of the software are being developed to promote collaboration and centralization of the forensic datasets. Digital radiology is a great asset and compatible with WINID3. DMORT also has the automated VIP system that includes WINID3 (http://www.winid.com/index.htm). Handheld computers, notebook computers, and laptops can all be employed in the collection and documentation efforts. Handheld digital recorders could store dictation information to supplement digital camera and video camera files.

The investigator must consider how and where to store the bodies. Particularly important are the containers for the bodies, the means to preserve the bodies, and a system to allow organized retrieval of specific bodies. Body bags are not always readily available, especially in large quantities. In these cases, sheets, temporary coffins, or even shipping containers may be used.

Although the preservation of the bodies is important, the investigator needs to collect any tissues needed for chemical studies before chemical preservation is used. Refrigeration is perhaps the best method of preserving the bodies until the investigation is completed, although charred bodies do not have the urgent need for refrigeration. Refrigeration is particularly important in warm climates, and the investigators may need to rent refrigerated truck trailers. Although the design of a typical truck trailer accommodates approximately 50 bodies, the inventory and retrieval process is easier if fewer numbers are stored in each vehicle.

Keeping track of more than approximately 20 bodies at a time is often difficult, and assigning one person to keep track of each body whenever it is out of the storage area is an effective quality control procedure. This person follows the assigned body as it proceeds through each stage of the identification process and keeps the labels and other paperwork in order.

In an effort to safeguard jewelry from looters, rescue workers often remove personal effects from bodies and place them in bags. Although this procedure may seem reasonable if the personal effects are placed in individual bags and labeled with the number of the corresponding body, the possibility still exists for errors in numbering. The situation in which two bodies have the same number readily illustrates the nature of problems that may be encountered. In any case, the identification investigator can only hope that the personal effects he or she did not personally observe to be attached or associated with a body were properly marked. During airline accidents, control of the personal effects of the fatalities and survivors is usually delegated to specially trained airline personnel.

Collection of Identification Data

The second phase in the investigative process focuses on data collection. This is a particularly intensive period for personnel, and the effective direction of efforts results in an uneventful and thoroughly successful investigation. Overcoming the initial inertia is one of the hurdles. People often seem to stand around waiting for something to happen, frequently not realizing that they are the ones who must take the first step. Figure 25-17 is a schematic of the overall flow of information and can serve as a visual guide to the following identification sections.

Who is Missing?

The investigator must accurately determine the answer to this question as early as possible. He or she must take immediate steps to obtain a list of persons believed to be missing and their last reported position. The identification methods to use, the types of additional assistance that may be needed, and the duration of the investigation depend on this list. Finding this information may be extremely difficult, especially in the case of natural disasters; in the case of aircraft accidents, however, this information should be available from the owner or operator in the form of crewmember assignments, flight manifests, passenger lists, and seating assignment charts. Manifest lists of affinity groups are usually the easiest to determine accurately. For example, when a military aircraft crashes, a manifest, or list of persons onboard the aircraft, will almost certainly be available. Unless a last-minute crew change occurred or passengers boarded the aircraft at the last moment without proper documentation, accurate information should be readily available from the flight operations department that dispatched the aircraft. However, problems can occur. For example, after the crash of an aircraft presumed to have only eight persons onboard, investigators recovered 17 feet from the wreckage. Without a preexisting list of persons suspected of being missing, the problem of identifying the disaster victims may be impossible. Disasters at airport, bus, or train terminals; hotels; and sports stadiums, circuses, and other entertainment sites are only a few examples of situations in which determination of who is missing is difficult. Almost every medical examiner's office that was large has had a body that remained unidentified until someone finally noticed that the person was missing and filed a missing person report. The problems are even more difficult when people use names other than their own when traveling. This immediately raises questions of illegal activity and foul play. These activities seem particularly prevalent in

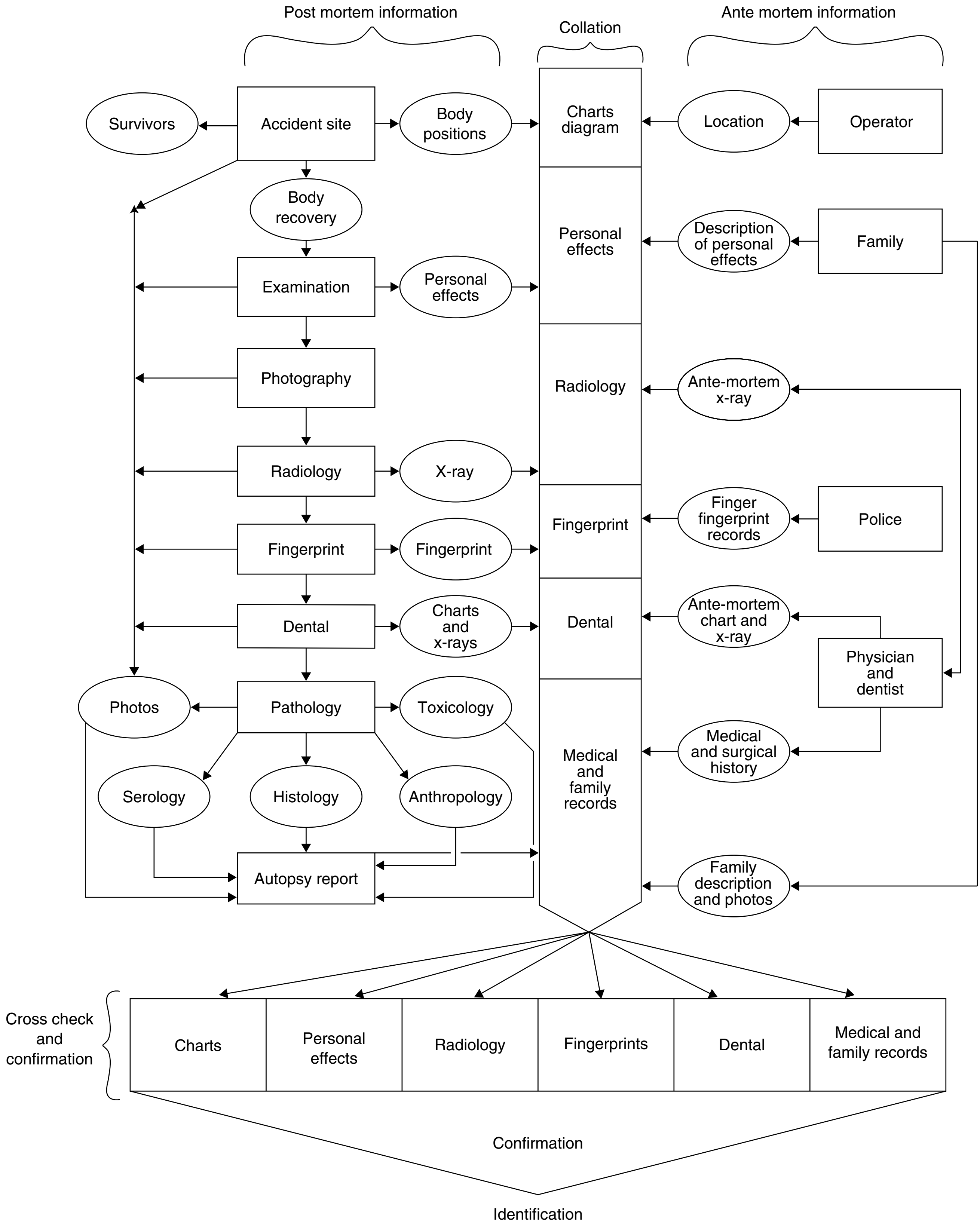


FIGURE 25-17 Diagram of the identification process information flow and overall organization (photo courtesy of Armed Forces Institute of Pathology).

international travel, but they also occur in domestic travel. Less sinister reasons are usually the case, such as when a large corporation makes travel reservations for one employee but at the last minute sends a different employee instead. Even such simple errors as misspelled names on a manifest can pose serious problems in discovering the identity of the missing person.

Antemortem Information

After establishing a tentative missing persons list, knowledge of the general condition of the bodies gained during cursory inspections in the preliminary evaluation phase will allow investigators to pursue the antemortem information needed for comparison with postmortem observations. They may seek some types of information more vigorously than other types, although still recognizing that even the secondary information is important. Medical and dental records may be more helpful than fingerprint records and information about clothing and personal effects in the case of severely burned and charred bodies. On the other hand, in the case of children, medical and dental records may have less importance. This underscores again the importance of the preliminary evaluation phase.

Antemortem data collection teams associated with the tasks mentioned in the previous text, in conjunction with the Family Assistance Center, have the hardest tasks within the ID center in determining who is involved and gaining the needed medical and dental records/radiographs.

Positive identification can be made only by comparison of observed features with those previously observed or recorded. Someone must find records of uniquely identifying characteristics for each of the missing persons if they are to be identified positively. If the investigators cannot obtain this information, positive identification will not be possible. Investigators can ask various sources, such as the missing person's family, friends, employer, physician, and dentist, as well as law enforcement agencies, for information and records. They should make every effort to obtain as much identification information as possible as rapidly as possible. An effective organization is essential to actively seek and to maintain appropriate chain of custody of the required antemortem records. Numerous checklists of desirable identification information are available. Although many of the commercial air carrier operators have detailed questionnaires that can serve as useful checklists, the investigators should inform the interviewers of the specific types of information required for that particular investigation and remind them that the people they interview seldom appreciate the urgency of the request for information and the necessary detail. The immediate acquisition of complete antemortem data is essential if the identification process is to proceed with dispatch and if it is to succeed at all.

Postmortem Information

The collecting of postmortem information actually begins with the first person at the disaster site. Although the bodies at some point must be recovered from the disaster site and transported to the mortuary facility where identification is to take place, under the best of circumstances the rescuers will leave the bodies *in situ* until the investigators arrive. Impressing the importance of this on rescue organizations should be part of any disaster plan.

Identification Techniques

Identification techniques include visual, fingerprint and footprint, dental, DNA, anthropology, and forensic radiology. Identification conclusions should be positive ID, findings consistent with, or unidentified. Body numbering systems should be abundantly simple: 1,2,3,4,5, and so on. Identification by association or exclusion should be avoided. Presumptive identification based only on personal effects should also be avoided. Make identifications utilizing science. In high G force mishaps with a fire, most identification will be by forensic dentistry or DNA. Depending on the availability of antemortem and postmortem material, Dental ID and Fingerprint/Footprint ID will be the fastest and least expensive. DNA will be dramatically more expensive and consume weeks and months of time. Funding will prove the limiting factor. Airline insurance carriers may make the financial difference. DNA ID may prove the best way to resolve the problem of fragment consolidation. The visual mode of identification is highly unreliable. Make identifications in every forensic mode possible within your financial constraints. The ID center chief should only sign out a case when all the sections have completed their work and corroborated each other's conclusions. Take the philosophies that: "None of us is as smart as all of us." "There are no mistakes until it gets out of the section." "Assume nothing." "Use participatory management." "You have one chance to do it right the first time." "There are no emergencies in forensic sciences . . . slow down and focus on teamwork and quality." (35,39)

Knowledge of the exact location of each body, its injuries, and its position relative to various parts of the wreckage and to other bodies can be helpful. Before removal of any body, the investigator should have someone photograph it, chart its location on a diagram of the disaster site, and apply an identifying tag. As mentioned previously there are numerous technologic advances that offer a wide variety of tools to document the evidence. Among the tools that may be used include GPS-enabled computers, digital cameras, and video cameras, digital voice recorders, notebook computers that can be directly written on, wireless networks and storage devices such as flashdrives. The investigator may be able to correlate the body locations with the duty positions of crewmembers or with passenger seat assignments as a preliminary identification procedure. It should be noted that identification by seat or duty assignment is merely a preliminary step and does not result in positive identification.

Fragmented bodies require special care in collecting, tagging, and identifying each fragment. Investigators must search the disaster site carefully to ensure that they have not overlooked any body fragments. Even small fragments of tissue may aid in identification; small fragments of dentition or printable skin may be the evidence needed to identify some of the casualties. In the example cited earlier, only eight people were missing after one crash, but investigators found body fragments that included 17 ft. Because no one knew of a ninth missing person, the entire process of identification was much more difficult and time consuming than if some clue to the identity of the ninth missing person had been known. DNA identification techniques will be used with extensively fragmented human remains.

Rescuers may not be able to recover all of the bodies in some instances, such as in disasters at sea. Investigators must then decide when to terminate further search efforts. They may have to resolve through other aspects of the investigation whether there may have been more victims than the persons reported missing and consider the possibility of foul play.

The information required for the documentation of identity can be provided in most cases using the following methods:

1. Color photographs of the body (clothed and unclothed)
2. Total-body radiographs (including all extremities)
3. Documentation of all scars, tattoos, deformities, and operations
4. Documentation of body characteristics (hair and eye color, etc.)
5. Documentation of all clothing, jewelry, and personal effects
6. Dental chart
7. Fingerprints and footprints
8. Blood type
9. Anthropologic measurements and estimates of height, weight, body build, age, race, and sex

Initial Examination

Although the initial screening examination of each body does not require much time, it frequently provides immediate clues to identity. The investigator should take particular care at this stage to correlate any associated injuries when removing photographs and labels, and describing clothing and personal effects. Although the personal effects group will investigate these items further, the information about them should be noted and made available to the investigators at each successive workstation. Dentures and other dental material are best left for subsequent examination and removal by the dental investigators.

Complete photographic coverage of this initial examination is important. Photographs of all aspects of the body, particularly specific identifying features of the face, ears, hands, feet, and tattoos, are especially helpful documentation, and the investigator should obtain them before and after removing clothing and personal effects. Additional photographic coverage should be available to document any noteworthy observations made at subsequent workstations.

Radiologic Examination

Radiologic examination is an increasingly important identification tool. Lichtenstein (40) demonstrated its value in screening for foreign materials and identifiable structures, in comparing antemortem radiographic examinations, and in evaluating injury patterns. Obtaining comprehensive radiographs of the entire body frequently pays unexpected dividends. Occasionally, metal fragments from old traumatic injuries or war wounds are demonstrated. In many cases, investigators can obtain further information concerning the circumstances of death and the nature of the forces involved from the interpretation of these radiographs. Rapid digital whole body radiographs with storage or telemetry of the results can be very helpful.

The identification value of radiologic examination is greatest in instances in which the deceased is younger than 25 years. In this age-group, the interpretation of ossification centers and closure of the epiphyses can give a close approximation of the age of the individual. For these interpretations, the often-overlooked radiographs of the hands and feet are essential.

Investigators can take advantage of travel time when they must travel long distances to the disaster site. When they will not arrive at the disaster site until after the bodies have been removed to mortuary facilities, they can save time by requesting that initial radiologic studies be obtained before their arrival. Dental and fingerprint consultation may be requested during this travel period. The radiographs, dental charts, and fingerprint records will then be available for immediate review when the team arrives. Additional or complementary radiographs may then be obtained if necessary.

Fingerprints and Footprints

The next step in identification consists of examining hands and feet for the presence of printable surfaces. Fingerprint identification is the first method of choice because it is one of the most accurate and reliable methods for the identification of unknown remains. Experienced investigators can examine fingerprints obtained from disaster victims and, using various coding methods, search the massive files that are kept at organizations such as the FBI in the United States. If records are immediately available, even the physician can make a preliminary comparison. Most countries accept fingerprints and footprints as positive proof of identification.

The use of fingerprints or footprints as a means of identification depends on the availability of previously known prints for comparison. Employers, police, and other government agencies can often provide antemortem fingerprints for comparison. Hospitals may have fingerprints of mothers and handprints or footprints of children appearing on birth records. Inquiry during the preliminary evaluation phase should reveal whether any of these antemortem records are available. Some countries keep no fingerprint records. In other countries, these records are available only for convicted criminals. In the United States, fingerprint records of many adults are available for comparison, but even the FBI's large file of records contains fingerprints of less than 25% of the population.

Even when no antemortem records are available, the investigator may still be able to obtain latent fingerprints from the missing person's home, office, or vehicle. Good latent prints are often found on objects such as drinking glasses, mirrors, windows, and doorknobs. Satisfactory prints from only the palm of the hand may be on a drinking glass; the investigator must take prints of the entire hand for comparison in this case. The FBI Disaster Squad identified one or more victims through latent fingerprint impressions in most disasters in which they assisted. These techniques are not for the unskilled, but knowing that the techniques are available may greatly shorten the process of identification.

The forensic pathologist or other identification personnel may be able to accomplish many simple screening procedures because comparison of good quality antemortem fingerprint records with sharply defined postmortem impressions is not difficult. In most circumstances, however, the professional assistance of trained fingerprint experts from a local enforcement agency or military police is advisable in obtaining both prints and records.

Even in badly burned or decomposed bodies, satisfactory fingerprints for comparison can often be obtained by special techniques. Badly wrinkled or macerated fingers can often be restored to printable condition by the injection of a fluid such as saline. When burn charring involves only the epidermis, scraping away the charred tissue may enable prints or photographs to be made of the underlying dermis. If the facilities to obtain prints are not available, the investigator may remove and retain the finger pads, fingers, or even the entire hand until prints can be made.

In the case of a badly fragmented body, the investigator must make a diligent search for fragments of printable tissue. In one severe crash, after which the investigators could find only minute fragments of tissue, a 1/4 in^2. portion of skin from the thumb of the pilot was found inside the control stick. This not only served to identify the pilot but also indicated that he was probably attempting to control the aircraft at impact.

Dental Examination

Dental identification is probably the most widely used method other than visual recognition for the identification of unknown remains. Dental techniques for the identification of disaster victims have become increasingly important. More people worldwide have dental records than have fingerprint records.

Hill (41) described the dental techniques used by forensic odontologists in the United Kingdom for identifying aircraft accident victims. Morlang (42) described the organizational structure, technical procedures, and methods of documenting dental findings used in the United States. The potential for computer-assisted comparison of the antemortem and postmortem records is particularly interesting. Computer programs allow comparison of other identification information such as age, race, sex, height, weight, hair and eye color, scars, blood type, and surgical implants.

The assistance of a dentist, particularly a forensic odontologist, greatly facilitates dental charting and identification. The postmortem dental charting should show, as a minimum, the presence or absence of each tooth, the presence and exact location on the tooth of any restorations (fillings), the shape of the restorations, and the presence of cavities. In cases of extensive traumatic injuries, radiographs of the whole body that were obtained at an earlier station in the identification process may aid in the location of dental material that traumatic forces translocated elsewhere in the body.

The dentist can remove any dentures at this time for possible correlation with antemortem dental materials. Dentists often inscribe the person's name or other identifying information on artificial dentures. In many cases, they recognize dental work that they performed and may recognize other characteristics of the person's mouth.

Severe head trauma often dislodges the maxilla, enabling it to be removed with only a scalpel. The dentist may need to remove the mandible and maxilla in some other cases for adequate exposure or further inspection, and if a body still remains unidentified at the completion of the investigation, the dentist should remove and retain the teeth for possible subsequent identification. The technique for removing the teeth intact is simple. With a Stryker saw, the mandible and maxilla can be removed easily, leaving the teeth undisturbed.

The widespread use of radiographic documentation of dental prophylaxis and the decline in the scope of fingerprint identification files are responsible for the great progress in dental identification techniques. Radiographs of teeth may be made to compare the shape of restorations, the location and extent of cavities, the shape of individual teeth and their root structure, or any preexisting abnormalities with antemortem radiographs. Comparison of the root structure of the teeth in antemortem and postmortem radiographs may establish identification even if no restorative dental work has been performed.

The introduction of dental radiographs into the identification process has eliminated the confusion that can follow when the dental chart does not accurately show the actual dental characteristics. In cases where the dentist verbally transmits observations to a technician, the possibility for error exists; it is not unusual to find *left* recorded when *right* was intended or *buccal* recorded when the actual location was *lingual*. The forensic odontologist can readily verify the correct positions by inspecting the radiographs.

Dental identification depends on the availability of antemortem dental records for comparison. As with fingerprint records, the dental records may not be immediately available. The investigator can save time by taking the radiographs and doing the dental charting of the victim while waiting for the antemortem radiographs and charts. Because dental records are not maintained in central, coded repositories, as are fingerprint files, finding dental records depends on a reasonably accurate missing persons list. Using this list, the investigator should obtain all available previous records, including dental charts, radiographs, casts, and impressions. Even when the actual dental record is not available, the missing person's dentist can provide the necessary information by telephone.

Victims who had dental work performed subsequent to the last known dental record present a difficult problem of identification. If a victim's dental record indicates that he or she has 32 teeth and no restorations, a victim whose third molars are absent would not seem to be a likely possible match without knowledge that the teeth were extracted subsequent to the date of the record available for comparison. The investigators must take great care to avoid eliminating possible identity matches by errors such as this, and comparison of more detailed anatomic observations of radiographs is usually helpful in avoiding these problems.

Postmortem Examinations

Pathologists discuss the radiographs with radiologists, review the antemortem records, and then perform thorough postmortem pathologic examinations at the next station. The radiographs may show surgical materials, contraceptive devices, or other items of personal effects that were overlooked previously, particularly in the case of burned bodies, and allow the pathologist to recover them for further examination. The postmortem examination should be thorough, and the pathologist should record all weights, measurements, and possible identifying features carefully and collect appropriate tissue specimens for possible toxicologic and serologic studies. The toxicologic examination of tissues or body fluids may reveal the presence of medications that the investigator can correlate with medical records to confirm identification. Anthropologic and histologic procedures may also be necessary for identification, but this requirement depends on the availability of antemortem data for comparison. Because the pathologist frequently does not know until some later time whether antemortem data will be available, he or she should consider collecting appropriate measurements and specimens of bone and tissue.

Documentation of body characteristics may serve to further narrow the possibilities of the identity of the deceased. The value of separating tall from short persons is obvious, but investigators often overlook the possibilities for comparing hat size, sleeve length, neck size, waist and inseam length, and shoe size. Measurements that may be affected by postmortem effects on soft tissue must be interpreted with great caution, but they are nevertheless of value in the subjective evaluation of the victims.

Many people have unique identifying body characteristics as a result of exposure to the environment. Other body characteristics may not necessarily be identifying, but they may facilitate further categorization. Categorizing characteristics include surgical scars (such as from an appendectomy), circumcision, and pierced ears, and many tattoos and scars are unique.

The investigator may compare hair obtained from a pillow or comb in a person's home to head hair on an unidentified body. The characteristics of an ear may be compared with those in an antemortem photograph or fingernail clippings found in the home with fingernails on the body. The use of these techniques is less common, and they tend to be last-ditch efforts.

Anthropologic Observations

The direct observation of findings in skeletonized remains (i.e., without resort to the techniques of radiology) may be possible. The investigator can determine age, race, sex, and stature from the interpretation of skeletal remains. Even in intact bodies, the pathologist may excise the pubic symphysis by using a saw and examine the opposing faces of the pubic bones for the presence of parturition pits, indicating a past pregnancy, or to determine age.

DNA

Recent advances in application of laboratory comparison testing of antemortem and postmortem specimens for DNA have changed the identification process to make DNA fingerprinting the dominant process being used. This new technique is especially important because fewer people have fingerprint records on file, and water fluoridation and improved dental care result in fewer readily identifiable dental characteristics. One of the principle advantages of DNA identification techniques is that they can be used with very small tissue samples or even bone. Until a number of years ago, DNA analysis was used only to reassociate body parts. This is still a valuable function and is part of the process at the CAMI to provide quality control of the submitted specimens for toxicology analysis, because some specimens may have been labeled incorrectly, or not labeled at all. However, the U.S. military has been collecting blood and oral swab samples from military personnel into a data repository since 1992, making DNA identification one of the most useful identification methods. The theoretic accuracy of DNA identification is much more reliable than any other method. Although some of the laboratory procedures still require particular care, the examinations yield reliable results for identification when conducted carefully by trained personnel. One of the original techniques, restriction fragment length polymorphism, is a laboratory procedure that requires six steps (43):

1. Isolation of DNA. DNA must be recovered from the cells or tissues of the body. Only a small amount of tissue—such as blood, hair, or skin—is needed. For example, the amount of DNA found at the root of one hair is usually sufficient.
2. Cutting, sizing, and sorting. Special enzymes called *restriction enzymes* are used to cut the DNA at specific places. For example, an enzyme called *EcoRI*, found in bacteria, will cut DNA only when the sequence GAATTC occurs. The DNA pieces are sorted according to size by a sieving technique called *electrophoresis*. The DNA pieces are passed through a gel made from seaweed agarose. This technique is the biotechnology equivalent of screening sand through progressively finer mesh screens to determine particle sizes.
3. Transfer of DNA to nylon. The distribution of DNA pieces is transferred to a nylon sheet by placing the sheet on the gel and soaking them overnight.
4. Probing. Adding radioactive or colored probes to the nylon sheet produces a pattern called the *DNA fingerprint*.

Each probe typically sticks in only one or two specific places on the nylon sheet.

5. DNA fingerprint. The final DNA fingerprint is built by using several probes (5–10 or more) simultaneously. It resembles the bar codes used by grocery store scanners.

When working with very small samples, which may have commingled with other persons' tissues, contamination is a very real possibility. In aviation accidents, deep muscle tissue samples are often preferred to minimize cross-contamination. In one accident, three legs were identified as having the same DNA fingerprint. Onboard the plane was a set of identical twins. Both twins had perished, and the recovery process only yielded three of the four legs. Some of the most common techniques that have expanded the utility of DNA-based analysis are restriction fragment length polymorphism (the technique is discussed in the above-mentioned example); polymerase chain reaction analysis (to amplify from extremely small samples); short tandem repeats (FBI); mitochondrial DNA analysis; and Y-chromosome analysis.

Much more information is available online with wiki-based searches and at http://www.ornl.gov/sci/techresources/Human_Genome/elsi/forensics.shtml.

Undoubtedly, as the technical barriers are overcome, functional genomic analysis will be added to the forensic repertoire of tools to assist in determining the circumstances affecting the humans in the accident sequence of events.

Personal Effects

Personal effects can provide clues to identity. These helpful materials may vary from specific information such as identification cards containing photographs and fingerprints to less specific items such as jewelry, clothing labels, and watches. Careful chain of custody throughout the identification process is important. Photographs are helpful for documenting each item, and the investigator can circulate the photographs among the identification groups or show them to relatives without having to handle the actual material excessively.

Laboratory Examination of Tissue

The investigator first examines the tissue grossly to determine its general appearance, texture, consistency, and the presence of any odor. This may allow him to determine whether the material is tissue and, if so, whether it is human and what part of the body it is from (44). The pathologist may be able to determine whether materials found at the crash site are mammalian by examining them under the microscope. The erythrocytes of all species other than mammals have nuclei. Figure 25-18 illustrates the nucleated erythrocytes from tissue found at the site of an accident caused by a bird strike. Serologic studies may be helpful (some of these are described later in the chapter).

The intensive effort during this data collection phase is critical. With tissue, observations must be documented

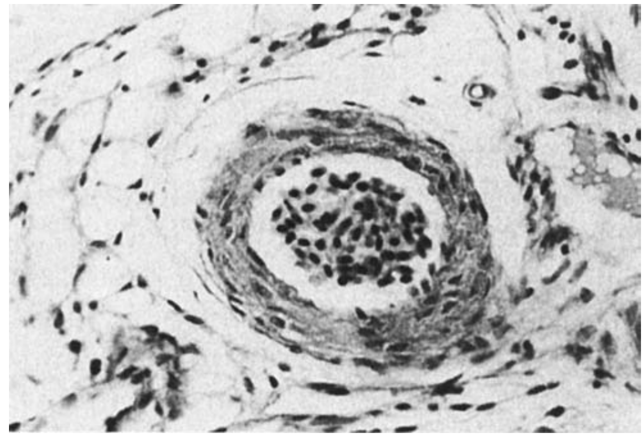


FIGURE 25-18 Nucleated erythrocytes from a bird-strike accident (photo courtesy of Armed Forces Institute of Pathology).

as quickly as possible before postmortem changes obscure them. The lack of suitable antemortem data for comparison will make much of the postmortem information useless, but the investigators risk incorrect identification of some of the casualties if they fail to document all possible identifying features.

Application of Identification Techniques

Certain techniques, such as the comparison of fingerprint, dental, and DNA records, are more reliable and provide definitive identifications directly. On the other end of the reliability scale are such characteristics as height, weight, skin color, and hair color that may be subjective, difficult to measure, and are subject to change; however, even combinations of these subjective characteristics may provide reliable and, in some cases, the only identification. The "odd-man-out" method (described in the section **Techniques**) is a practical screening technique that can lead to identification in carefully selected instances even in the absence of identifying features. The careful application of these techniques and avoidance of the pitfalls enable even an inexperienced investigator to collect valuable information to simplify and shorten the identification process.

A method of identification can be successful only if it adequately meets each of the following three requirements: the body feature must be unique, it must be attached to the body, and a suitable antemortem record must exist. Uniqueness, attachment, and what constitutes a record can vary. Although fingerprints are singularly unique, the presence of pierced ears is not. Teeth are attached to the body, but personal effects such as jewelry can be removed. Antemortem records can vary from vague personal recollections to records prepared specifically for the purpose of casualty identification.

Certainty of Identification

One issue in the course of the mass disaster identification process is how certain the identification of each victim must be. How positive are the investigators that they have made correct identifications? As a practical matter, in some disasters in which bodies are severely fragmented and burned or little antemortem information is available for comparison, identification of all of the casualties may not be possible.

Probably everyone has, at one time or another, seen an apparent acquaintance at a distance only to find on closer observation that the identification was incorrect. Perhaps this occurred because the physical resemblance between the suspected and actual persons was great or because the observer based his or her determination on limited information. An observer can seldom be certain about identification when he or she observes only a part of the whole. For example, the identification of a known person from the posterior aspects of the head is possible, but this identification is not usually as reliable as when the observer makes the identification after seeing the person's face. Hair length is not a reliable basis for distinguishing men from women, although facial hair such as beards and mustaches may be helpful.

The reasons for the certainty in identification are more than academic. Of course, social and moral reasons pressure the investigator to identify casualties and return them to their families. In different societies, pressure may be expressed in a variety of ways. Some cultures are meticulous in the desire to identify all casualties with certainty; in other cultures, the pressure is more to release a body to the family before some religious deadline. In the latter circumstance, it often seems that the desire is for the determination of certainty of death rather than for the certainty of identity of each individual body. Some governments have issued individual death certificates on the basis of the aircraft manifests and held mass burials when they presumed that all persons onboard were dead.

Careless identification techniques can initiate a cascade of errors that may result in extraordinary embarrassment. The problems usually begin with insurance claims, survivors' benefits, and other disposition of personal property. In one case, the haste in providing early identification and release of the body of a prominent political figure was for naught (McMeekin, *personal communication*, 1985). Investigators had to have the body exhumed when it was discovered that they had incorrectly identified it. Cases of borrowed clothing and dog tags also have occurred. The importance of clearly understanding the distinction between definitive and supportive evidence of identity is readily apparent.

An important question that the investigator must answer at the onset of the investigation is, "How, with all of the various methods of identification that are available, can I most efficiently achieve certainty of identification of these casualties?" Four general categories of procedures are available: definitive, secondary, cumulative, and confirmatory. Obviously, any one procedure may fall into more than one of these categories, depending on the circumstances in which it is used. Identification conclusions should be positive ID, findings consistent with, or unidentified.

Definitive Methods

The methods of identification that stand alone as means of identification are known as *definitive methods*. Theoretically, these methods assume that only one person can have a particular set of characteristics. As a practical matter, investigators can seldom, if ever, achieve this degree of certainty. As a result, they tend to settle for a degree of certainty of identification on the basis that the probability of any other person having those particular characteristics is low. Labels in dental restorations that contain the deceased's name and identifying number are examples of "absolutely" definitive methods of identification. Of course, even this evidence is not 100% reliable, unless the investigator is certain that the deceased or the preparer had no motive to falsify the identity, that no mistakes occurred in the antemortem preparation of the labels or in the postmortem examination process, and that the antemortem records are correct.

All methods of identification involve the comparison of observed characteristics of the bodies with known or reported characteristics of persons missing or presumed to be dead, and definitive identification of a person occurs when investigators identify a sufficient number of objective features that belong to the missing person and only to that person. Theoretically, two people may have certain characteristics that are similar enough to be identical for all practical purposes. For this reason, the investigator must assign a degree of probability to each method of identification. The greater the number of identical characteristics found, the more certain the probability that the identification is correct. For example, the probability is much greater if 25 matching fingerprint or dental characteristics are present than if the only comparable feature is blood type A.

How many presumptive correlations are necessary to approximate a definitive identification? No set number applies unequivocally to all circumstances. Correlation of three characteristics such as height, weight, and hair color are usually not as corroborative as the correlation of the evidence of surgery and other scars, congenital defects, and dental restorations. On the other hand, if only one of the missing persons weighed more than 150 lb, and if he or she happened to weigh 250 lb, this might be a very significant identifying characteristic indeed.

A high degree of negative correlation may also be of great value in limiting the number of persons under consideration. For example, if investigators determine that 20% of the victims have blood type A, the missing persons known to have blood types AB, B, or O are not likely to provide a match.

Secondary Methods

Secondary methods of identification are those methods that use characteristics that could belong to more than one person and that therefore do not by themselves give a high degree of probability of certainty of identification. On the other hand, in many instances, secondary methods that are considered in isolation to have a low probability may provide almost certain identification if sufficient numbers of separate methods can be combined. Secondary methods are most useful when they are used in combination with the cumulative methods described in the following section. Examples of secondary materials and characteristics are age, sex, hair color, and color and type of clothing. Secondary methods can give highly reliable results, but the positivity seldom approaches that of the definitive methods. The limited value of determining that the sex of an unidentified body is male when all of the missing persons are male is easy to appreciate; likewise, a similar determination is of little assistance when half the number of a large group of missing persons are male. On the other hand, the finding of a male body is highly significant when only one male is missing.

Cumulative Methods

Especially when using secondary methods of identification, the investigator needs to somehow increase the probability that identifications are correct. Using cumulative methods to analyze several secondary characteristics, the combined probability of certainty of identification increases. In the hypothetic example in Table 25-4, finding a male body cannot result in definitive identification; similarly, finding an edentulous body cannot result in definitive identification. A male body could be either person A or person B, and an edentulous body could be either person A or person C. However, by cumulating these findings, assuming that these three bodies do, in fact, represent three missing persons, an edentulous male body can be only person A. Therefore, methods that have an inherently low probability of definitive identification can be combined using cumulative techniques to provide certain identification.

Fingerprint identification is a widely used method of definitive identification, but this technique is actually an example of the cumulative identification methods. The theoretic possibility of any two persons having identical sets of fingerprints depends on the degree of cumulation used. Dental examination, another of the commonly used means of "positive" identification, could also be considered a cumulative method, and one could likewise calculate degrees of certainty of this identification method.

Confirmatory Methods

The use of confirmatory methods is another variation of the cumulative technique. For example, using the hypothetic situation described in Table 25-4, having identified body A using the cumulative methods, the investigator may find it possible to obtain definitive identification. Fingerprint or dental records may be available for comparison, or, in unusual cases, investigators may obtain latent fingerprints from the missing person's home for comparison.

TABLE 25-4

Example of the Cumulative Identification Method

Victim	*Sex*	*Dental Data*
Person A	Male	Edentulous
Person B	Male	Present
Person C	Female	Edentulous

Selecting the Identification Techniques

How are investigators to select which of these methods to use in particular situations? The practical answer is that they must use every method that they reasonably can in every case. Even in the situation where definitive methods are readily available, investigators must always be on guard against the possibility that there may be an error in the records or the observations.

Missing persons lists are frequently incorrect in at least some aspect (Morlang, *personal communication,* 2007). When commercial modes of transportation are involved, these errors are almost a routine occurrence.

Errors may occur because of fraud or mistake; even criminal misconduct may occur. Certain errors may occur as a normal course of business and may not be detected without knowledge of the business practices. When using prenumbered forms for recording observations of the unidentified bodies, an observer can very easily record findings on an incorrect form. When many bodies are involved, especially when identifying features that are not readily apparent (as in severely burned bodies), observations may be correctly charted but may be from a different body. Clerks may file records in an incorrect folder or, when using wall charts, may place an "X" in an incorrect column.

How are investigators to avoid the pitfalls that these errors can induce? They cannot entirely. They must always be alert to the possibility that errors may exist, and they must continually take steps to minimize the effect these errors will have on the overall investigation; they should take whatever steps are possible to detect the existence of errors. Investigators should be especially wary of methods that tend to remove a missing person from consideration too early.

From a practical standpoint, three general rules are helpful:

1. Do the best you can with what is available.
2. Do the easiest things first.
3. Do not release a body before making definitive identification.

Data Analysis

Data analysis occurs in the third phase of the investigation, as working groups continue to evaluate the data they collected in the data collection phase. The investigators who observed the postmortem findings are best suited to analyze the data, but substantially fewer people are necessary. Reducing the total number of personnel by 50% or more is usually possible at this stage.

Analyzing the data consists of integrating the information from the antemortem records and the postmortem observations. Of particular importance is organization of the techniques for recording, charting, and storing antemortem and postmortem data so that investigators can easily find the necessary information. The early installation of appropriate quality control procedures and careful consideration of which identification techniques, such as spotting, mix-and-match, exclusion, or odd-man-out, will be most productive and will increase the efficiency of the data analysis process.

Quality Control

The antemortem records almost invariably contain some inaccuracies, and other errors will probably occur in the observing and recording of postmortem findings. Transposition of left and right occurs frequently in medical records, and estimating the height, weight, sex, or age of fragmented or severely burned bodies can be extremely difficult. Recognizing the probability of these errors caused by human frailty allows the investigator to plan to avoid the most serious pitfall, misidentification as a result of an irreversible error.

Early adoption and strict adherence to quality control procedures will minimize these errors. More than one observer should confirm each postmortem finding, and each of the working groups should reexamine observation notes from the preliminary examination and from other working groups. Each member of the working group should verify all of the postmortem evidence from a matching antemortem record before making identification, and making this evidence available to all of the other working groups provides an additional measure of control. Rigid adherence to these seemingly tedious and often redundant procedures will save valuable time in the long run.

Morlang (42) described a computer program used to assist in the identification of victims of the 1977 Tenerife disaster, and computers are now essential for data collection and analysis. Converting the antemortem and postmortem data to an acceptable format for the computer requires training and practice. Opportunities to test these computer applications under actual disaster conditions are infrequent; therefore they must be part of disaster planning and exercises. If the equipment such as computers, GPS position locators, and other electronic devices require cooling, charging, or other period maintenance then this will affect the resources needed to support their use. It will also potentially change where various stations are set up considering the inaccessibility of some remote accident sites. Nevertheless, small, portable, yet powerful computer systems are increasing in availability and acceptance, and the logical nature of the information flow procedures in the data analysis phase make them ideally suited for their application in facilitating the scientific identification of disaster victims.

Techniques

The methods of analyzing identification data fall into four general categories. Spotting depends on investigators remembering characteristics observed at the postmortem examination when they encounter similar features as they review the antemortem records. The initial review of the records frequently reveals several obvious identities, and investigators may even correctly identify some victims whose postmortem characteristics were recorded incompletely, inaccurately, or perhaps not at all.

The mix-and-match technique consists of the logical manipulation of the records into groups that have characteristics in common. Selecting all of the casualties that have a particular characteristic in common, such as age, sex, or race; that have dental or fingerprint information available; or that have unique items or personal effects such as rings or watches which will allow the investigators to focus their attention on more likely identification matches. They should prepare lists grouping these possible matches and make their lists available to all of the other working groups for possible confirmation. As this "mixing" occurs, identity "matches" may become apparent, but this preliminary match must not be the sole basis for positive identification.

Identification by exclusion is another data analysis technique, but investigators should apply it with great caution. When two crewmembers are missing and investigators have positively identified one, the temptation is great to conclude that the second body found within the wreckage is the other missing crewmember. This conclusion may be correct in many instances, but it becomes infamously wrong when the missing persons list turns out to be incorrect. Investigators should avoid the temptation to regress to identification by exclusion when the identification process progresses more slowly than expected. They may need to reexamine the bodies or resort to other methods of identification.

Investigators may be able to identify some victims by a process of elimination if they are certain that all of the bodies have been recovered. If they are reasonably certain that the missing persons list corresponds to the identities of the recovered bodies, the problems of identification are much simpler. In this situation, the degree of certainty necessary for identification need not be as great. Identification by exclusion cannot occur, however, unless all of the bodies have been recovered and the list of missing persons is complete.

The exclusion techniques are also useful in other ways. Tables of exclusion are often helpful for the early categorization of identifying features by the mix-and-match method. Determination of sex is usually easy, and this may exclude a large number of possible missing persons from further consideration. The investigators can exclude person C on the basis of sex and person B by the presence of teeth, and the cumulation of these observations greatly increases the probability that the victim in the example in Table 25-4 is person A.

After first applying the best and most positive methods in attempting to identify victims, a few bodies without definite identifiable features may still remain. In these cases, methods that would not otherwise establish identification may be useful when investigators apply them to a large number of bodies using the odd-man-out technique to produce good evidence of identification. Mason (45) proposed the odd-man-out technique for the evaluation of distinctive injury patterns in reconstructing the cause and sequence of events in an aircraft accident. The logic process of Mason's injury analysis technique applies equally to the preliminary identification of fatalities, in which it relies on the cumulation of observations or, in some instances, the absence of certain observations, and in some applications is an extension of the exclusion method of identification.

Initial screening examination of the bodies usually reveals that some of the bodies have characteristics for which the investigators will almost certainly discover comparison data. Pregnancy and the presence of a glass eye or an artificial limb are identifying data that identification questionnaires seldom seek, but finding this information can be extremely valuable. The presence of any one body with features different from all other bodies found in the wreckage sets the odd-man-out process in motion.

Simplification of the identification process by the odd-man-out method does not require that the characteristics be totally unique. If all of the passengers and crew were male except for one female flight attendant, the investigators could presumptively identify the only female body found as the female flight attendant. Investigators occasionally find an identifying feature that almost certainly must be unique, a feature that only one person in the whole world could possibly have, but, unfortunately, will find nothing in any antemortem record of the missing persons to substantiate the characteristic.

Investigators must exercise great care to avoid eliminating a particular body or missing person from consideration prematurely on the basis of a characteristic that was not unique or that was described improperly. This caution applies especially to the application of the exclusion and odd-man-out methods.

Conclusion Phase

The conclusion phase begins when a working group makes a presumptive identification. Other members of the working group check the observations to confirm the presumptive match first and then refer the presumptive match to other working groups, where confirmation will lead to preliminary identification.

The working group may be unable to reach a presumptive identity determination, but their list of possible matches may be helpful to another group. When a second group reviews the list, their observations may provide additional clues to focus on the identities. This aspect of the conclusion phase overlaps somewhat with the data analysis phase.

Each working group examines all of the data. If they find no inconsistencies, the responsible senior investigator then reviews the observations that support the match before confirming the positive identification. The senior investigator should release no body before each working group reviews the identification data and he or she confirms the determination. Adequate records should reflect this observation and review process.

Recommendation Phase

The recommendation phase involves more than just identification. Usually, investigators must prepare to make other recommendations as well. They must decide when to abandon search efforts for additional bodies or body fragments, especially in circumstances such as disasters at sea, in which rescuers may be unable to recover all of the bodies; they must determine whether, particularly in the case of fragmented bodies, there may have been more victims than persons reported missing and whether continued searches for additional information will be productive. They must also provide other investigators with recommendations about whether to pursue any possibility of foul play as a cause of any of the casualties.

Investigators must finally determine what to do about any unidentified bodies or body parts that remain. They must thoroughly reexamine each of the fragments to ensure that they have not overlooked any clues to identity, and they may be able to match some of these fragments with previously identified bodies by means of blood type, injury patterns, or hair and fingernail characteristics. This problem is another reason for investigators to take special care to document findings and maintain records throughout the identification process.

Investigators should thoroughly document the remaining body fragments using photographs, radiographs, diagrams, and written descriptions. Retaining mandibles, maxillas, and fingers makes subsequent dental and fingerprint comparison possible. The remaining body fragments should be retained for a reasonable period of time, the length of which depends on the location and condition of the fragments and the likelihood of finding suitable antemortem information for comparison.

Whether to dispose of the remaining fragments or to bury them depends on the bulk of the tissue, whether identifying characteristics are present, and whether the investigation accounted for all of the missing persons. Burial of each unidentified body, or of all associated body parts in the case of fragments, in individual numbered sites will facilitate subsequent exhumation should the investigators discover additional identifying information.

Recommendation for Forensic Documentation of Flyers

The realization that one might be in an aircraft mishap is not an easy topic to address mentally. For fliers, however, the possibility exists. Without a death certificate, family survivors may go through many years of legal battles before resolving estates and getting on with normal life. To help avoid this, fliers should ensure that full personal antemortem forensic data is available somewhere. This should include well-documented medical and dental records, a list of all physicians and dentists who have treated them, a list of all hospitals where admitted, a list of maternal relatives, current dental radiographs, a fingerprint/palm print card, a footprint card, and a properly preserved blood specimen for DNA analysis if needed. There are companies that provide such options for parents concerned about missing children and these can be used by aircrew in the absence of a formal program. The airlines and other aviation-related companies should mandate antemortem record documentation for their flight crews.

A very simple low technology option is the wearing of a metal ID tag such as those issued to military personnel. Frequently, even in the most destructive of aviation accidents, the feet will be preserved, often still contained within footwear. Military flyers might place an additional tag inside the flying boot on the medial side with a short chain attached to the top eyelet.

INJURY PATTERN ANALYSIS

Determining the sequence of events in an aircraft crash is essential to any crashworthiness investigation, and injury pattern analysis focuses on that determination. Various combinations of injuries form certain characteristic patterns that relate to the sequence of events in the accident, and careful analysis of these patterns, often explain otherwise obscure circumstances of an accident. Trauma, the environment, and preexisting diseases are the significant factors the investigator must consider. This analysis, although rarely of importance in the determination of the cause of the accident, unless it is a medically related accident due to incapacitation or impairment, should always be undertaken in every accident investigation. Tools are available to assist the medical investigator in reconstructing the accident sequence of events using the visual display of data, which greatly facilitates the processing of complex injury data and allows rapid comparisons to be made.

In large aviation accidents with many fatalities, investigators are challenged by collecting the data and satisfying the investigative purposes quickly so that bodies can be released after identification and injury documentation. There is a need to develop and maintain well-trained teams of individuals, who can expedite the field collection of data, and to deal with the stressful circumstances of the survivors and next of kin, as well as address the various regulatory, legal, and humanitarian concerns occurring at the same time.

Every accident should be examined for information that may improve crash survivability, and this search must always consider the following elements:

- Was there occupiable volume?
- Were the impact forces within the capability of the human body, *properly restrained*, to tolerate and survive?
- Was the body adequately restrained? Did the restraint system function properly?
- Was there some local lethal circumstance of the cockpit or cabin that directly caused death due to penetration of the body or being in the strike zone of the *properly restrained* body during impact?
- Was the postcrash environment the cause of death, due to fire, smoke, water, toxin, or some other hazard?
- Use a categorization system such as CREEP (Container, Restraints, Environment, Energy absorption, Postcrash) factors.

An online example of this list can be found in the United States Naval (USN) Flight Surgeons Guide at the following URL—http://www.iiimef.usmc.mil/medical/FMF/FMFE/FMFEref/fs_man/CHAPTER%2024.html.

Tolerance and Injury

The tolerance of each part of the body to injury varies considerably. The force may have no residual effect, may result in minor injury, or may produce irreversible or even lethal injuries. The ultimate consequences of force that amputates an arm are quite different from those of force that, when applied to the neck, results in decapitation.

Although humans have a definable tolerance to injury, much confusion exists in the literature as to what constitutes an acceptable degree of injury. One controversy concerns whether greater effort should be spent on preventing fatal injuries rather than less serious ones. The number of fatalities from crashes is relatively small compared with the number of injuries, and the total cost of treating the injuries is much greater than the cost of dealing with the fatalities. Accepting some fatalities may be the price paid to reduce more frequent and costly injuries.

The better approach gives equal consideration to the prevention of injuries and fatalities. Although evaluation of the injury tolerance issues may appear difficult, the investigator must avoid any first impulse, when confronted with fragmented bodies and wreckage, to conclude that survival would have been impossible. Even if the investigation authorities classify the accident as nonsurvivable, there is still much important data that can be obtained by studying both the injury and cause of death patterns in the fatalities, and the injury patterns of the survivors. In an accident where there is total loss of life and considerable body fragmentation, there is still value in cataloging and plotting in two or three dimensions the information gained from the identification process, assigned seating, postmortem findings [e.g., effects of cyanide (CN) or carbon monoxide], and injury patterns because this information may aid other investigators in crash vector analysis or determining the sequence of events.

Injury Pattern

An injury pattern is simply the enumeration of injuries that a victim sustained during or as a result of a crash and the categorization of the injuries by anatomic area, or physiologic function. After investigators determine the specific event that caused each injury pattern, they can prepare charts to use in comparing the pattern of injuries observed in one person with those seen in others. They can compare the injury patterns of casualties in the same aircraft accident or compare the injury patterns in one accident with injuries observed in another crash. Finding many burned bodies near an exit in an aircraft destroyed by fire may suggest obstruction or malfunction of the exit, and bodies or parts of the aircraft located far from the main wreckage suggests in-flight breakup of the aircraft. As mentioned previously with respect to the AIGIS, CAD programs have been used to display the injury patterns graphically in two or three dimensions, in conjunction with the seats and aircraft structures. The information gathered from each individual in the accident is kept in a database and queries are run on the data, which are then displayed visually by the CAD program in relation to the aircraft. This type of forensic documentation holds great promise for assisting in the information flow in mass disasters because the CAD program can be used to display any structure (building, vehicle, subway, etc.) within which the injury or death information can be portrayed and viewed from any angle. Some of the shock of displaying such unpleasant information is mitigated by the use of anthropomorphic representations of people and the use of color to encode various components of information, while the actual photographs of the data are stored online for recall at any point.

Investigators must document each injury pattern carefully and correlate it with the circumstances of the accident. This information is essential to making any modifications that will prevent similar injuries in the future. Because few injuries are specific for aircraft accidents, accident investigators may apply general forensic pathology techniques in interpreting the injuries.

A number of factors directly influence the specific injuries and patterns of injury. Decelerative forces, environmental factors, and the structural configuration of the aircraft produce injuries. Incisions, lacerations, fractures, thermal injuries, and interference with respiration are specific types of injuries, but the severity of each injury may range from minimal to fatal.

The most difficult problems facing investigators are the determinations of (a) exactly when an injury occurred, (b) the nature of the force that produced the injury, and (c) whether the observed injuries are the result of the impact forces or an artificial change induced by the postcrash environment. Did the injury occur before or after death, or did it perhaps even exist before the crash occurred? How much force was required to produce the injury, and how was the force applied? Is the injury pattern misleading, being in fact something other than what it appears to be?

Injuries have misled investigators because they erroneously appeared to be classic, diagnostic accident injury patterns when they were actually caused by entirely different factors or were artifactual. These preexisting injuries and artifacts are probably the most frequent cause of erroneous interpretations of injury patterns and the sequence of events in the crash.

Injury patterns and specific injuries are directly related to the following:

1. The magnitude, duration, direction, and pulse shape of the acceleration forces
2. The cockpit or passenger compartment configuration
3. The nature of the accident and subsequent occurrences
4. The occupant kinematics in the accident, particularly those relating to the restraint systems

Acceleration Forces

The magnitude, duration, direction, and pulse shape of acceleration forces affect the pattern of injuries and are major factors in determining injury tolerance. Certain levels of force produce minimal injury, whereas greater force may produce transient injuries. Still greater force may produce irreversible injury or even death.

Eiband (46) suggested that the magnitude of tolerable acceleration is inversely related to the duration of its application. Human volunteers tolerated acceleration forces of great magnitude for short periods. Colonel John P. Stapp experienced more than $-45\ G_x$, on a rocket sled. Early ejection system experiments exposed human subjects to more than $25\ +G_z$, with vertebral fractures as the only resulting injuries.

Many people have survived apparently impossible circumstances of high G deceleration such as falls of more than 300 m. The factors that contributed to survival in these cases are poorly defined, but perhaps the high velocity resulted in reduced pulse duration and increased tolerance. By contrast, only 1 G in the G_z acceleration field may be fatal within a period of several hours. These two examples, representing the extremes of the acceleration scale, illustrate the complexity of the problems associated with tolerance to acceleration.

Cockpit or Passenger Compartment Configuration

The configuration of the compartment may restrict expeditious exit after the crash. The occupant may strike some part of the cockpit or passenger compartment and sustain fatal injuries in what would have otherwise been a survivable accident. Loose objects set in motion by the crash forces may strike the occupant, or he or she may strike the fuselage, or be crushed by it, or by other objects in the immediate vicinity. The likelihood of death and injury increases significantly if external objects penetrate the occupant space or if the crash forces crush the occupiable (livable) space. Engine, transmission, and still-turning rotor blades may penetrate the occupant space and cause fatal injuries during helicopter crashes. In a small commuter nonfatal accident in 1991, there emerged a pattern of injury to several passengers that was related to failure of the seat stanchion flange bolts used to fasten the seats to the floor tracks, which was in turn due to the improper type of flange bolt part being installed in the seat assembly. Although the calculated impact forces were in excess of seat standards, it could be seen clearly in the on-scene portion of the investigation that there was only one failure mode that the seats had experienced, at least with respect to the integrity of the seat-track-floor interface. Only seats that had had passenger(s) with a total weight above a certain amount had failed, and the failures were all through a hole in the flange bolt. (Figure 25-19A, B, C) When the seat manufacturer was contacted, they indicated that someone had inserted the wrong type of flange bolt into the seat assembly. The type of bolt used was one for the attachment of bulkheads, and the hole in the bolt was to allow a cotter pin to be inserted allowing the bolt to be tightened. Therefore, the part which had additional manufacturing steps to create the hole was more expensive. Although both bolts were certified

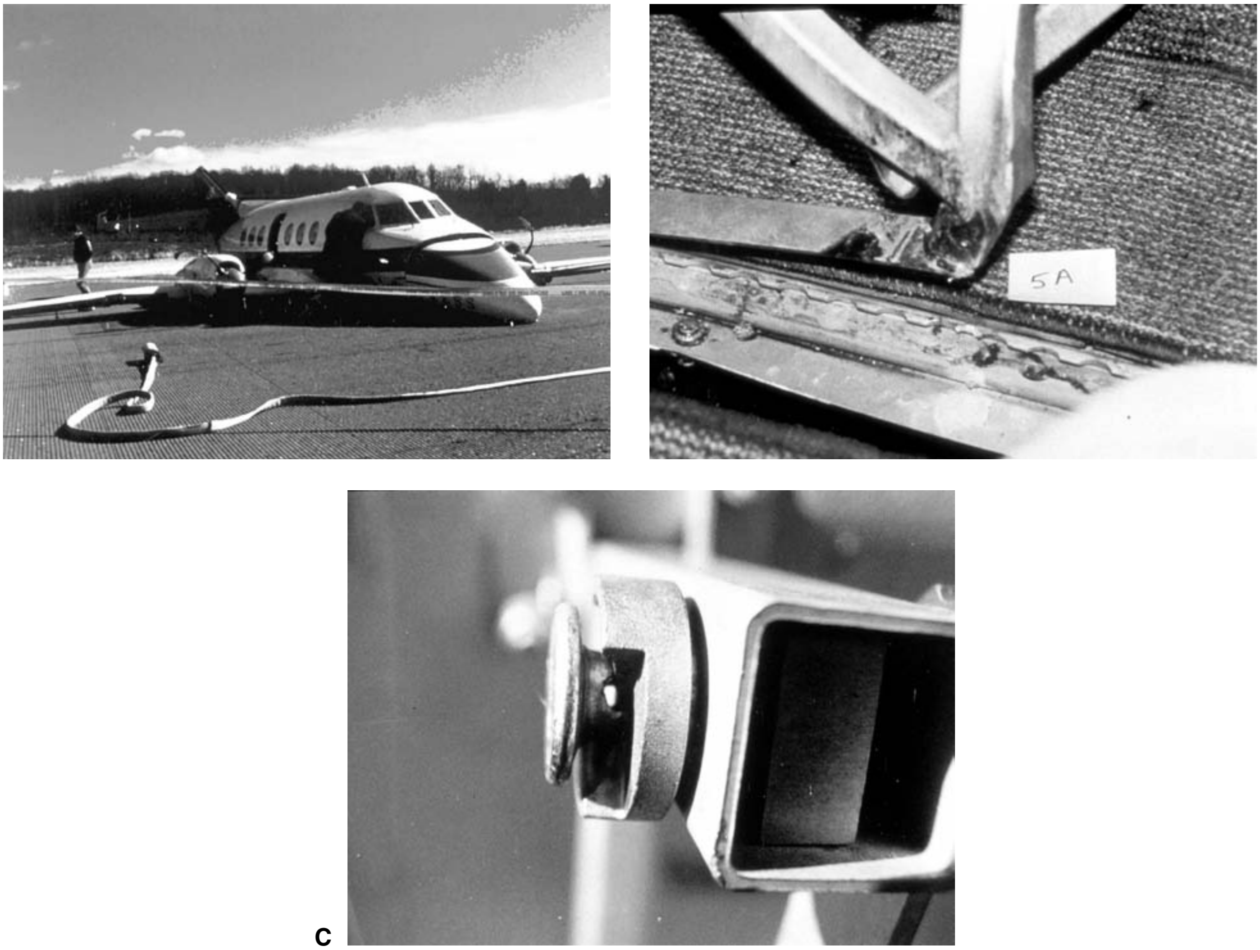
A B C


FIGURE 25-19 Nonfatal commuter crash investigation of seat assembly failure pattern, (**A**) aircraft wreckage, (**B**) seat stanchion and track assembly, (**C**) intact flange bolt, but is for bulkhead attachment points not seat assemblies (photos courtesy of NTSB/Civil Aerospace Medical Institute).

as strong enough according to testing requirements, all the bolt failures observed in the accident were through the drilled hole. In this case, the recommendation led to the correct, less expensive, and stronger product being used.

Historically many Cessna aircraft had occasional problems with the seat sliding back on takeoff due to wear in the seat rail holes that led to several accidents. The FAA issued Airworthiness Directive AD 87-20-03 R2 calling for seat track and latching inspections. A secondary latching system was developed to prevent the problem. The Aerocommander 112 and 114 seats could come loose in a crash due to flexing of the bottom of the seat, with the restraint pins coming out of the tracks.

These restraint design issues are examples of what should be looked for, or thought of, in terms of failure modes that should be part of every investigation. Occam's razor applies also to determining the cause of aviation mishaps; the explanation with the minimum needed assumptions should be accepted primarily. Still, one should remember that given the opportunity to examine other potentially even unrelated aspects of the investigation, findings may turn up that prevent a future injury occurrence.

Nature of the Accident

The nature of the accident and subsequent events explain many injury patterns. In general, the types of injuries seen in helicopter accidents are different from those that result from crashes of fighter or large transport aircraft. This is due in large part to the differences in operational activities of each of these aircraft and to the relative size differences between these aircraft. The amount and type of structures surrounding the occupants are very different between general aviation aircraft, commercial aircraft, and military aircraft for both fixed-wing and rotary wing types. The velocities and the crash force energies to be dissipated are also different for these classes of aircraft.

The nature of the accident and the sequence of events influence the character and severity of crewmember injuries after ejection from an aircraft. Bird strikes, in-flight explosion, striking part of the aircraft or ejection seat after exiting the aircraft, parachute-opening deceleration, or impacts during or after landing may produce similar injury patterns. Investigators must seek trace evidence such as paint scrapings or tissue fragments from suspected contact points to reconstruct the sequence of events.

Mason (45) suggested the odd-man-out technique for the evaluation of injuries. He compared injuries received by multiple fatalities in a single crash with those received by fatalities in separate crashes and looked for similarities in injury patterns. If investigators find dissimilar injury patterns, they must determine what the individuals with each injury pattern were doing that was different. Finding cabin crewmember injury patterns that are similar to passenger injury patterns suggests that the cabin was prepared for the crash, but dissimilar injury patterns would indicate that the occupants might not have anticipated the crash. The finding of leg fractures may explain why many occupants did not exit the aircraft, although fire may not have developed until many minutes after the crash.

Occupant Kinematics

Many factors influence the trajectory an occupant follows during a crash. The magnitude and direction of the acceleration vector, the shape of the acceleration pulse, the amount of crushable material in the aircraft, and the nature of the seat and restraint systems can vary the trajectory considerably and greatly influence the force applied to the occupant. Investigators must evaluate all of these factors carefully before reconstructing the occupant kinematics during the crash. Special techniques, such as computer simulation, may be helpful. Normograms of crash force analysis are also available for computer use.

Various types of protective devices and equipment, such as specially designed seats and other restraint systems, helmets, and protective clothing, frequently modify injury patterns. Most protective systems have many components, and the failure or inadequate design of almost any of these system elements can exponentially increase the force applied to the occupant and lead to injury or death. If an attachment point of a seat or restraint system to the basic structure fails, the occupant will feel an acceleration force of shorter duration but of much greater magnitude. Force magnification also occurs when the restraint system fails or, because of elasticity or plasticity, allows the occupant's motion to extend to lethal areas outside the protective envelope.

Traumatic Injuries

Head Injuries

Head injuries are the most frequent cause of death in aircraft accident victims. These injuries often result when the head, neck, and upper torso flex over a lap belt because they are unrestrained by a shoulder harness system. This allows the unprotected head, chest, and extremities to strike exposed structures, resulting in serious or fatal injuries.

The skull provides reasonable protection to the cranial contents, but an impact that damages the integrity of the cranial system or transmits the impact force to particularly sensitive areas is often fatal. Concentrations of impact force are particularly lethal, and designs that distribute the force greatly increase the magnitude of the impact the head can withstand.

Certain preventive measures can reduce, if not entirely prevent, these head injuries. Helmets can provide energy absorption and distribute the impact force, and shoulder restraint systems can reduce the range within which the head could strike cockpit objects. Aircraft designers can avoid introducing possible injurious impact surfaces into the cockpit during the development phase.

FIGURE 25-20 Transverse fracture of the base of the skull (photo courtesy of Armed Forces Institute of Pathology).

Linear fractures of the skull tend to occur in the plane in which the force was applied. This has sometimes led investigators to believe erroneously that transverse fractures of the base of the skull, extending from ear to ear and across the sella turcica, could result only from a blow to the side of the head (Figure 25-20). At least as frequent a cause of the transverse fractures, however, are blows to the bottom of the skull, transmitted through the mandibular rami when the face impacts with an instrument panel.

Ring fractures—fractures around the circumference of the foramen magnum—may result from force transmitted up the spine in positive G_z impacts. Although this fracture pattern can occur from force transmitted from a blow to the top of the head, this possibility is rare. Because the center of gravity of the skull is forward of the spine, a blow to the top of the head tends to produce flexion, resulting in asymmetric application of force to the foramen magnum. This results in anterior cervical fracture and a Jefferson's fracture (see section **Spinal Injuries**) rather than ring fractures.

Skull fractures tend to be subtle, and investigators may not be able to see them without careful observation. They must meticulously remove the dura before concluding that no skull fractures are present. Blunt trauma of greater magnitude may produce eggshell fractures of the skull. Even more severe impact, especially when the upper torso is not restrained or when the upper torso restraint system fails, results in partial or complete decapitation.

Head injuries sometimes mislead investigators if they rely on examination of the strike envelope alone in considering

FIGURE 25-21 Buckling of fuselage at impact was the primary cause of injuries in this accident (photo courtesy of Armed Forces Institute of Pathology).

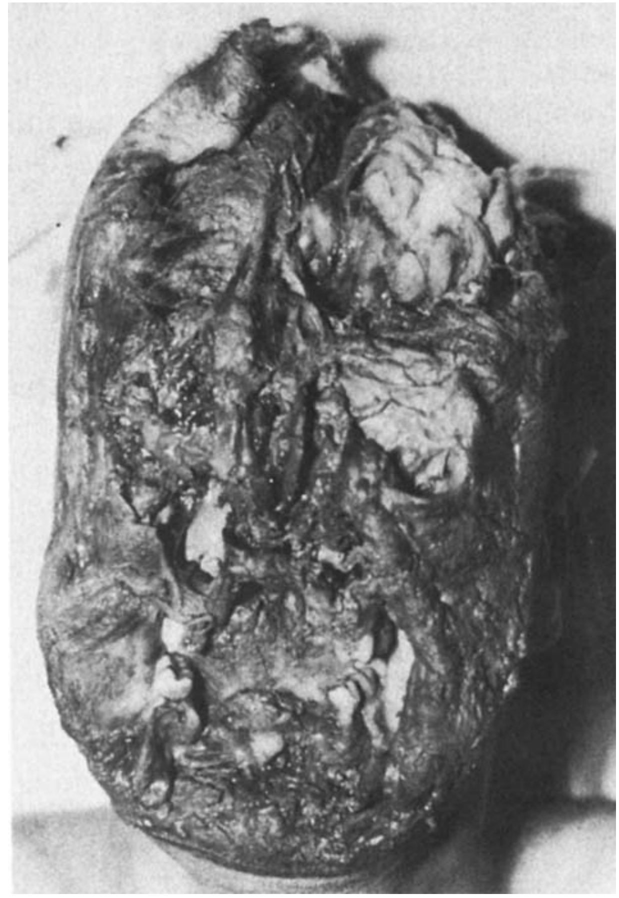


FIGURE 25-23 Head injury as a result of walking into the tail rotor of a helicopter (photo courtesy of Armed Forces Institute of Pathology).

the possible causes of the injuries. They should consider the possibility that collapse of the aircraft structure or impact with loose objects produced the injury. Figure 25-21 illustrates such a case. The pilot of a small single-engine plane sustained fatal head injuries during the crash. Brain tissue was on the instrument panel, and investigators found imprints of the knobs and instrument dials on the pilot's face. The investigators believed that the aircraft was not equipped with an upper torso restraint system, and they suspected that this deficiency allowed his upper torso to flex forward and his head to strike the instrument panel, which resulted in the fatal head injuries. Examination of the cockpit of the wrecked aircraft, however, clearly indicated that the injuries resulted from the pilot's head being crushed between the instrument panel and the aft overhead cockpit bulkhead despite use of shoulder harness restraint. This occurred when the aircraft fuselage buckled at impact. An example of the patterned abrasions on the face from the instrument panel can be seen in Figure 25-22 from a general aviation investigation where no torso restraint was used.

Unusual head injuries may lead to erroneous conclusions, especially when the investigator is not fully cognizant of the circumstances of the accident. Figure 25-23 is a photograph of a crewmember who walked into the tail rotor of a helicopter. Figure 25-24 illustrates a blowout fracture of the skull from increased intracranial pressure that resulted from steam production as the postcrash fire heated the skull.

FIGURE 25-22 Patterned abrasions from contact with the radio in the instrument panel on the face of a pilot not wearing a shoulder harness. (Photo courtesy of Civil Aerospace Medical Institute.)

FIGURE 25-24 Fire artifact-steam blowout fracture of the skull after a runway collision between two airliners in 1991 (photo courtesy of Civil Aerospace Medical Institute).

Internal Injuries

Crash forces can damage the internal organs of the chest and abdomen by any of several mechanisms, and this damage may result in death if prompt medical and surgical assistance is not available. Because the internal organs are relatively unrestrained and are suspended only by attachments within the chest and abdomen, they move during the impact sequence in a manner that may be quite different from the deceleration of the body as a whole. This frequently means that decelerative forces acting on these organs are much greater than those acting on other, more restrained body parts. Internal tears may be caused by shearing forces applied as a result of differences in the mass of various tissues, and organ asymmetry may introduce torsional forces.

The direct application of force to internal organs as a result of penetration of the body cavities by external objects, or as a result of impact with cockpit structures or seat belts, can cause serious injuries. Overlying bony structures, such as the ribs and pelvis, provide a measure of protection to many of the internal organs, but other organs are more vulnerable.

The ribs, sternum, scapulae, and thoracic vertebrae, being bony structures, protect the organs of the chest. Application of approximately 2,250 kg of force by a restraint belt may produce rib fractures. The jagged ends of a broken rib may lacerate the heart and lungs and even some of the abdominal organs, such as the spleen, kidneys, and liver.

Approximately 13% of aircraft accident fatalities involve significant cardiovascular injury. Missiles, broken ribs, or portions of the aircraft cockpit or controls may penetrate the chest and puncture the heart or major blood vessels. The heart or great blood vessels may burst as a result of being compressed between the sternum and vertebrae or from force transmitted from compression of the chest and abdomen. Once adequately designed cockpit enclosures, torso restraints, and head protection systems are in use, the tolerance of the cardiovascular system will determine the magnitude of the decelerative force that humans can survive.

Tears of the aorta are frequent findings in crash fatalities that have little external evidence of injury, and the pathologist must carefully examine the heart and the aorta *in situ* and avoid introducing artifactual lacerations. Aortic rupture as an isolated finding is more common just distal to the left subclavian artery, but in cases of cardiac injury, 65% of the tears are in the ascending aorta just above the aortic valve. The origins of the subclavian and carotid blood vessels at the aortic arch provide relatively fixed attachment points for the heart and descending aorta, and even if a restraint system prevents significant movement of the upper torso, decelerative force may cause the heart and descending aorta to swing forward, like pendulums, during a crash. Because the heart is asymmetric (the left ventricle is more muscular than the right ventricle), the deceleration may concentrate torsional forces and produce tears in the ascending aorta. Concentration of the shearing forces that result from the different deceleration rates of the heart and descending aorta, from deceleration of the aortic arch, produces tears of the ascending and descending aorta near the insertions of the ligamentum arteriosum.

Blunt force applied to the abdomen can produce lacerations, tears, or rupture of the abdominal organs and blunt trauma to the thorax or abdomen may rupture the diaphragm. Although both the liver and spleen receive some protection from the rib cage, the liver is the more vulnerable of the two organs to impact injury. An improperly positioned or loosely fitted seat belt, or a soft seat cushion, may allow a seat occupant to slide under, or "submarine" beneath, the restraint system. This increases the frequency of spinal fractures and rupture of abdominal viscera.

Spinal Injuries

Examination of the spine provides the investigator with especially valuable information, particularly the evidence needed to determine the direction and magnitude of impact.

Vertebral fracture occurs frequently with vertical forces (positive G_z) greater than approximately 20 G (U.S. Army Crash Survival Guide USARTL/TR-79-22). Compression fractures of vertebrae occur from the imposition of high positive G_z forces, especially in ejections from fighter aircraft or hard landings in helicopters. Two thirds of subjects sustain vertebral fractures at G levels greater than 26 G_z, but vertebral fracture can occur at forces as low as 10 to 12 G, especially when the positioning of the spine is not entirely vertical. Multiple compression fractures in one individual are unusual and seldom occur at levels less than 35 G_z.

Forces of G_y or G_x in excess of 250 to 400 g may produce shearing fractures of the vertebrae, especially in high-speed crashes (Figure 25-25). The mass of the denser vertebral end plate, which is greater than the mass of the vertebra, may contribute to this injury pattern. When crash force is applied, this inertia creates much the same situation as can be shown by the elementary demonstration of inertia in which a book is placed on a piece of paper to illustrate that the paper can be removed without dislodging the book.

Pure compression fractures (positive G_z), shearing fractures (either positive or negative G_x or G_y), or Chance fractures (G_z) are rarely seen. Most vertebral fractures result from combined x, y, and z force vectors but especially from the x-axis and z-axis. This causes a fracture pattern much like that which would be produced by a crowbar, with compression of the anterior portion of the vertebra and pulling apart of the posterior bony or ligamentous portions in tension (Figure 25-26). This results because the force vector effectively places the fulcrum in the anterior portion of a vertebra. In a runway collision accident in 1991 between two commercial aircraft, there was a secondary collision with a building (Figure 25-27). The negative G_x force, evident from the patterned abrasion on the chest in Figure 25-28 due to the control yoke in Figure 25-29, and the design of the shoulder harness contributed to the fractured thoracic vertebrae (Figure 25-30). The shoulder harness, which attaches in front to a standard four-point restraint buckle, crosses over the shoulder and descends to an inertial reel at the back of the pilot's seat (Figure 25-31). The seat

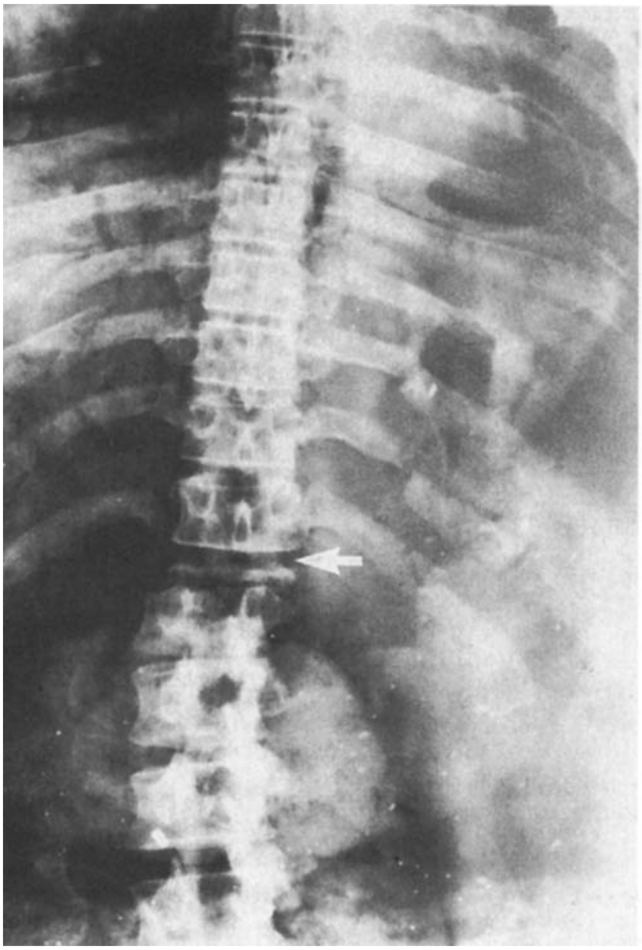


FIGURE 25-25 Shearing fracture of a vertebra (photo courtesy of Armed Forces Institute of Pathology).

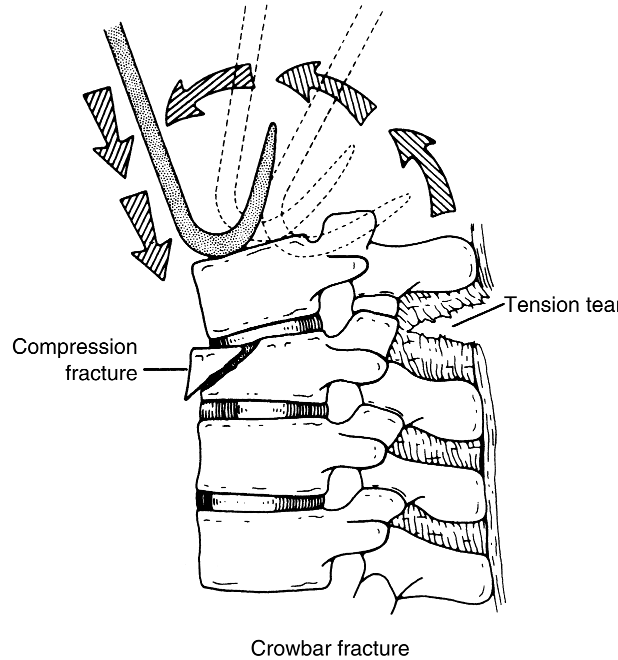


FIGURE 25-26 Mechanism producing crowbar fracture of a vertebra.

back is low and below the level of the shoulder; therefore, the decelerative forces are increased in magnitude and changed in direction loading the spine, causing the anterior wedge compression fracture. Seat belt design in the U.S. Army Crash Survival Guide USARTL/TR-79-22 published in 1980 indicates that the shoulder harness should be positioned at the level of the spine or upward no greater than 30 degrees in order to prevent this type of force magnification (Figure25-32). Although this was not the cause of death for the pilot, because there were other crush injuries to the head, it highlights the usefulness of a complete injury analysis. If the pilot had not been otherwise harmed, he would still have had to egress the aircraft with a broken back due to his restraint system. This example of clinicopathologic correlation highlights the need for a thorough postmortem examination, to discover and document findings that might otherwise go unnoticed, due to their lack of importance to determining the manner of death.

Various crash circumstances may apply force to the neck and cervical vertebrae, causing fractures and dislocations. Windblast during ejection from an aircraft may cause the aviator's protective helmet to rotate and the edge of the helmet to strike the neck, much like a guillotine, causing fracture or dislocation of cervical vertebrae. Aircraft wiring and parachute lines entangling the neck are examples of mechanisms that result in "hangman" fractures of the pedicles of the C2 vertebra (Figure 25-33). Impact to the top of the head may cause Jefferson's fracture, which consists of vertical splitting of the ring or lateral masses of the C1 vertebra, and lateral displacement of fragments of the vertebral body. Dissection of the anterior and posterior neck, followed by careful examination, is often helpful in these cases.

Injuries of the Extremities

Injuries to the extremities result from the flailing of unrestrained extremities and from impact with structures;

FIGURE 25-27 The Boeing 737 fuselage came to an abrupt stop against this building after a runway collision with another aircraft, which is below the larger aircraft (photo courtesy of Civil Aerospace Medical Institute).

FIGURE 25-28 Patterned abrasions on the chest of the left-seated pilot at autopsy, which were caused by the pilot's control yoke (photo courtesy of Civil Aerospace Medical Institute).

FIGURE 25-30 Wedge compression fracture of a thoracic vertebra discovered at autopsy (photo courtesy of Civil Aerospace Medical Institute).

these injuries are seldom fatal unless complicated by other factors. Excessive loss of blood may result from multiple injuries, and injuries of the extremities may prevent or impair escape from a hazardous postcrash environment. If seat structures collapse on the feet, ankles, or legs of passengers, then they will have difficulty or delays evacuating from the aircraft.

Flailing of arms and legs during ejection from an aircraft may generate sufficient force to cause fractures. The flailing motion, much like that of cracking a whip, concentrates the force more distally, producing fractures of the tibia, fibula, radius, and ulna more frequently than of the femur and humerus. Femoral fractures may result from force applied by the anterior edge of the ejection seat.

Unrestrained extremities may contact aircraft structures within the strike envelope with sufficient force to produce injuries. The legs and arms may strike the instrument panel or a seat in front. A "dashboard femoral fracture" may result from the knee impacting with the instrument panel. Although extremity injuries are of little help in estimating the impact velocity and the parameters of the crash pulse, they may produce patterns that will indicate to the investigator exactly what structure the occupant struck.

Injury patterns of the hands and feet may provide good evidence of who was controlling the aircraft at the time of the crash, especially if other data correlate with the patterns of injury. The rudder pedal may leave a reversed imprint (of the manufacturer's logo or other pattern on the rudder pedal) on the sole of the shoes or boots of the pilots at impact. The best evidence of control is fracture of carpal, metacarpal, tarsal, and metatarsal bones, with associated patterned lacerations of the palms and soles of the hands and feet. Coltart (47) described "aviator's astragalus," fractures of the talar neck in pilots of aircraft with toe brakes. Fractures of the phalanges may be helpful indicators of control, but they are less reliable. Dummit and Reid (48) described unique tibial shaft fractures in helicopter pilots. Similar tibial fractures also occur in pilots of other aircraft.

Injury patterns in passengers of the lower limbs and feet may be due to seat collapse in front of them. The resulting

FIGURE 25-29 Left seat control yoke with fracture of the left grip (photo courtesy of Civil Aerospace Medical Institute).

FIGURE 25-31 Cockpit seats with relatively low seat backs. Left side seat shoulder belts were cut during rescue efforts (photo courtesy of Civil Aerospace Medical Institute).

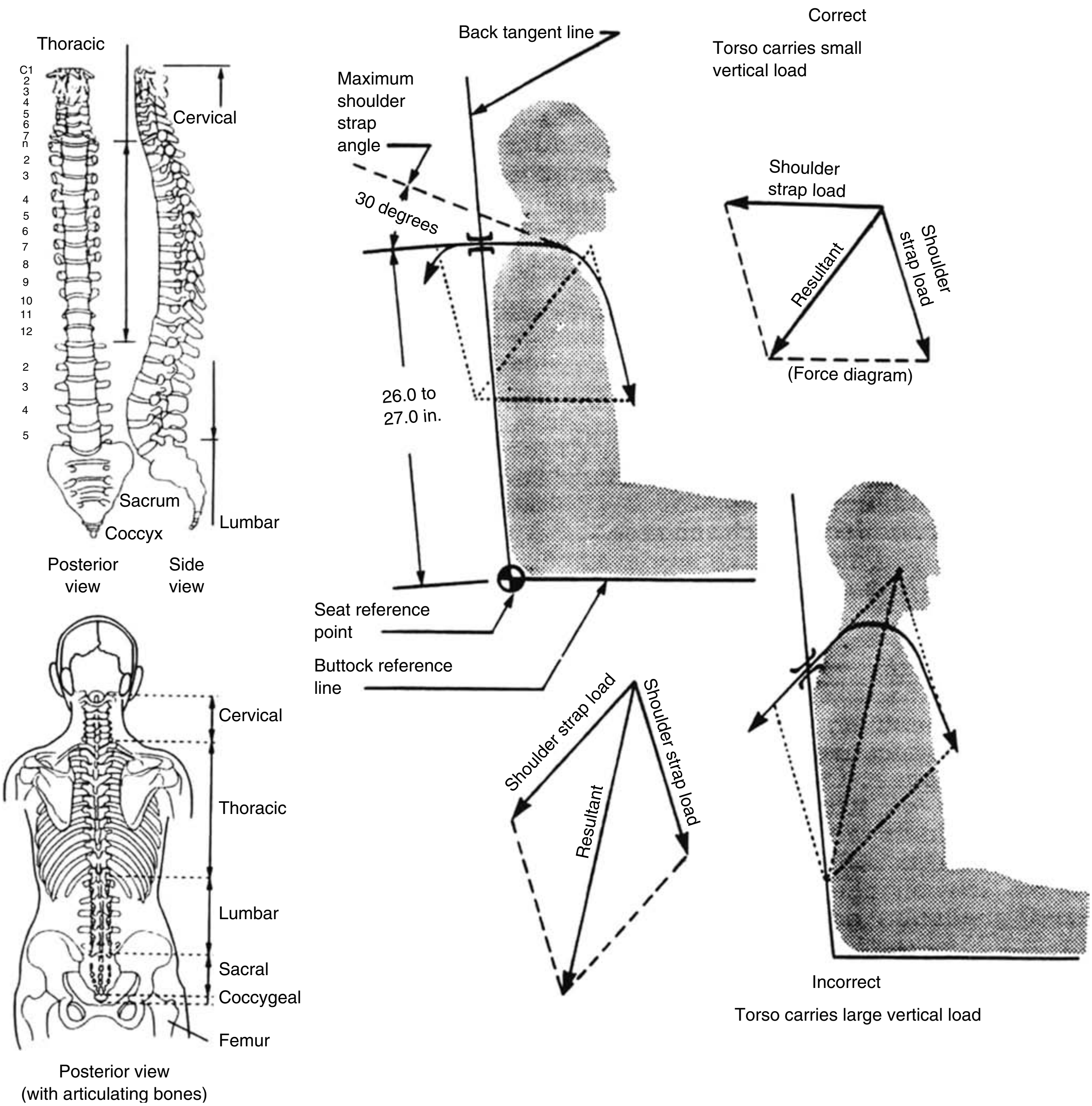


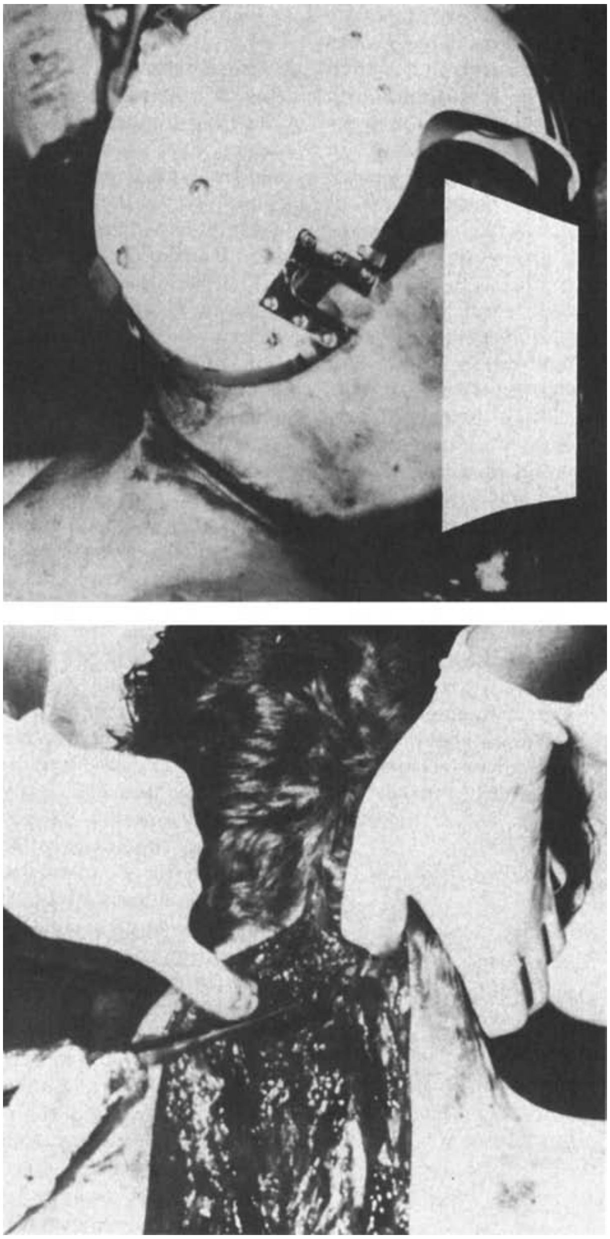
FIGURE 25-32 Excerpt on shoulder harness geometry from the U.S. Army Crash Survival Guide (USARTL/TR-79-22).

fractures may preclude egress, and in the presence of a postcrash fire, may lead to their demise. Head injury can be correlated to failure of the overhead storage bins.

Case Summaries

Nonsurvivable Crash Forces and No Occupiable Volume

In 1992, there was a multiple fatality accident near the Grand Canyon. The flight was a sightseeing flight (DCA92MA040) using a Cessna C402C in a nonscheduled commuter flight (14 CFR Part 135). The full report should be read by investigators as an excellent example of how to use all available resources to reconstruct an accident sequence of events. The analysis of onboard passenger videotapes allowed the discovery of key factual findings to guide the investigation into the human factors aspect of the accident causation. In terms of survivability Figures 25-34, 25-35, and 25-36 show a similar aircraft to the accident aircraft. Figures 25-37, 25-38, and 25-39 show the extensive vertical deformation noticed in the accident aircraft after it struck in a flat attitude. It should be remembered that there is some degree of springing back (perhaps 20%) called *oil canning* of the aluminum fuselage so the final volume in the



A

B

FIGURE 25-33 Cervical fracture resulting from entanglement with helmet microphone cord: **(A)** Anterior dissection and **(B)** posterior dissection (photos courtesy of Armed Forces Institute of Pathology).

photographs are not representative of what the volume of the cabin was diminished to during the impact sequence. The fuselage would have been even flatter during the dynamic impact sequence, with a time scale measured in milliseconds. With no occupiable volume available to the occupants, this accident was nonsurvivable. In addition, there were high vertical G loading forces due to the LOC of the aircraft. The pilot did not maintain the minimum control speed (VMC) with an engine inoperative; therefore, a VMC roll over occurred shortly after departure with high + GHz impact forces, and deformation of the fuselage made this accident nonsurvivable. Videotape captured preflight information,

FIGURE 25-34 Sistership Cessna 402C left front quarter view (NTSB photo).

useful engine variation sounds, key fuel-flow information from the instrument panel, propeller nonfeathering, and the immediate events after takeoff to impact.

Survivable but for Restraint Failure

In 1976, a Cessna C182C being used as a public use aircraft in Oklahoma City by an Internal Revenue Service (IRS) agent ran out of fuel and while engaged in an off-airport landing hit wires 65 ft above the ground in a residential area. The aircraft struck inverted with very little deformation of the cabin area (Figure 25-40, Figure 25-41). The restraint attach point on floor failed, causing the pilot to be nonrestrained and was the direct cause of death (Figure 25-42 and Figure 25-43).

Survivable but for Lethal Cockpit Environment

The fatigued, noninstrumented-rated pilot became spatially disoriented in a Piper PA-28 during a turnaround after entering inadvertent instrument meteorologic conditions (IMC). Figure 25-44 shows the fuselage after impact with intact occupiable volume. Upon impact with the ground, the passenger struck the yoke, which broke (Figure 25-45) and penetrated the chest causing death (Figure 25-46). The pilot

FIGURE 25-35 Sistership Cessna 402C interior view (NTSB photo).

FIGURE 25-36 Sistership Cessna 402C left side view (NTSB photo).

was interviewed and gave details of becoming disoriented in an area with thunderstorms and having very little sleep in the last 24 hours (FTW76AF126).

Survivable but Trapped, Egress Not Possible

The pilot of a corporate Grumman American AA-1 operated under 14 CFR Part 135 ran out of fuel and attempted to land in a field (CHI76AC031) (Figure 25-47). He survived the impact but was trapped for 18 hours before rescue. In that aircraft, the seats attach directly to the main wing spar (Figure 25-48), therefore the pilot's spine sustained a dynamic overshoot of crash forces; Figure 25-49 shows the seat bottom deformed by the round main wing spar and Figure 25-50 is an x-ray showing the fractured lumbar spine.

Nonsurvivable, Evidence of Flying by Flight Control Related Injuries or Markings

A De Havilland Twin Otter flying as a parachuting operation crashed on departure with 16 deaths and 6 serious injuries in 1992 (LAX92MA183). The postmortem examination of the pilot's shoes showed a reverse imprint of DH transferred from the rudder pedals to the soles of his shoes.

FIGURE 25-37 Postimpact front view showing high degree of fuselage crushing, with remaining static volume in the photograph greater than was available to occupants during the dynamic impact sequence, the oil canning effect (NTSB photo).

FIGURE 25-38 Postimpact rear view (NTSB photo).

These examples are just some of the varied types of patterns that the medical accident investigator will encounter, and should be aware of, to maximize the collection of information from the consequences of the mishap. These cases where the injury patterns do not contribute to the underlying cause of the mishap were chosen to focus on the consequences of the mishap. If for a different *causal* reason a similar aircraft should impact the ground, the same injuries might be expected if one does not learn from crashworthiness discoveries and implement improvements in the cockpits and cabins of aircraft to promote crashworthiness. Elsewhere in this chapter, and in other sources and references cited, are techniques that might be used in relation to determining the cause of the mishap.

Environmental Factors

Environmental factors can contribute to the cause of an accident, can cause injuries, and can modify the appearance of injuries. Hypoxia, decompression, bird strikes, adverse weather conditions, fire, and water are some of the most significant hazards.

Hypoxia

Hypoxia may occur suddenly, as in cases of rapid decompression at high altitude, or may be more insidious, as in prolonged flight at intermediate altitudes of 3,000 to 4,500 m (10,000–15,000 ft). Information such as flight-planned altitude and ATC radio transmissions, or the CVR, may provide

FIGURE 25-39 Postimpact right rear quarter view (NTSB photo).

FIGURE 25-40 Cessna 182C inverted at crash site, note that the cockpit space is intact; lack of fuel prevented a postcrash fire (photo courtesy of Civil Aerospace Medical Institute).

key clues to suggest the incapacitation of crewmembers by hypoxia. The laboratory determination of lactic acid in the brain may provide confirmation, although the specimens will not likely be available for timely analysis due to the remoteness of many accident scenes. There may be other synergistic toxins that make hypoxia a possible factor in an accident, such as carbon monoxide, CN, or even carbon dioxide (dry ice) from the cargo area or the galleys where it is used to cool beverages.

There have been several well-publicized hypoxia incidents and accidents worldwide that highlight the fact that investigators need to maintain alertness for such factors in accident investigation and for pilots to maintain their high-altitude physiology training. (www.ntsb.gov/recs/letters/2000/a00%5F119%5F119.pdf)

FIGURE 25-41 Cessna 182C cockpit and cabin area are intact, seats are intact. Restraints are visible and require careful examination (photo courtesy of Civil Aerospace Medical Institute).

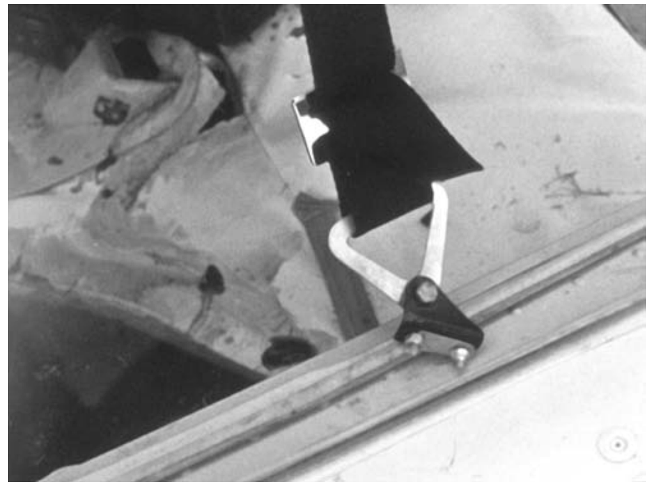


FIGURE 25-42 Pilot's lap belt restraint attach point is loose in the cabin (photo courtesy of Civil Aerospace Medical Institute).

Case Summaries

A Helios Airways Boeing 737-31S sustained total loss of 115 passengers and 6 crewmembers on board due to hypoxia on August 14, 2005.

The aircraft departed Larnaca, Cyprus bound for Prague, Czech Republic by way of Athens, Greece. The FDR records a decompression alarm at 14,000 ft. As the aircraft passed 16,000 ft, the captain reported a Takeoff Configuration Warning and an Equipment Cooling system problem. The aircraft had been cleared to flight level (FL) 340. Over the next 8 minutes, there were several communications that ceased as the aircraft ascended through 28,900 ft. Thereafter there were no radio communications. Passenger masks deployed in the cabin at 18,200 ft. The aircraft leveled and flew by autopilot on its intended route. It flew over Athens International Airport and entered a preprogrammed VOR holding pattern.

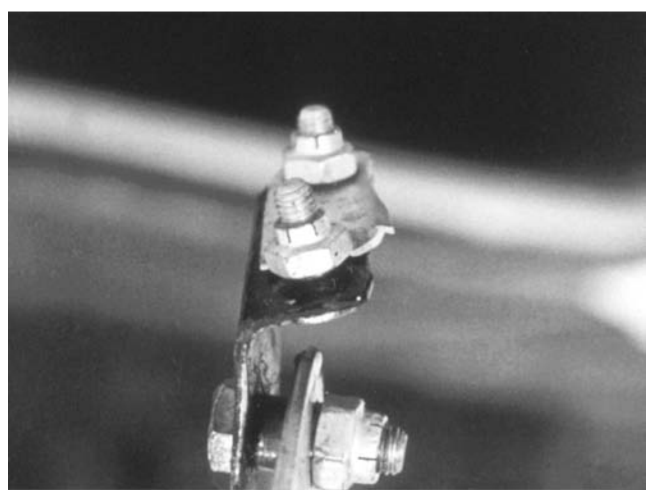


FIGURE 25-43 Close-up of fracture surface which, as is common, traverses bolt hole openings. Fracture surface can be examined for evidence of overload failure, metal fatigue, or manufacturing defect (photo courtesy of Civil Aerospace Medical Institute).

FIGURE 25-44 Piper PA-28 fuselage after spatial disorientation accident which is largely intact (photo courtesy of Civil Aerospace Medical Institute).

FIGURE 25-46 Postmortem photograph showing entrance wound to chest of passenger where the broken yoke pierced the chest leading to death (photo courtesy of Civil Aerospace Medical Institute).

Intercepted by two military aircraft, it was observed that the captain's seat was vacant and the first officer's seat was occupied with an individual slumped over the controls. A person, not wearing an oxygen mask, entered the cockpit and sat in the captain's seat approximately 17 minutes later. One minute later the left engine flamed out, and subsequently after 10 minutes, the right engine flamed out. Two mayday messages were recorded on the CVR (not even broadcast on the radio) 4 minutes after the left engine had flamed out due to fuel exhaustion. The aircraft impacted the ground approximately 3 minutes later.

The direct causes cited by the Air Accident Investigation and Aviation Safety Board (AAIASB) of the Hellenic Ministry of Transport and Communications were:

- Nonrecognition that the cabin pressurization mode selector was in the MAN (manual) position during the performance of the Preflight procedure, the Before Start checklist, and the After Takeoff checklist
- Nonidentification of the warnings and the reasons for the activation of the warnings (Cabin Altitude Warning Horn, Passenger Oxygen Masks Deployment indication, Master Caution)
- Incapacitation of the flight crew due to hypoxia, resulting in the continuation of the flight by the flight management computer and the autopilot, depletion of the fuel and engine flameout, and the impact of the aircraft with the ground

The latent causes were:

- Operator's deficiencies in the organization, quality management, and safety culture
- Regulatory Authority's diachronic inadequate execution of its safety oversight responsibilities

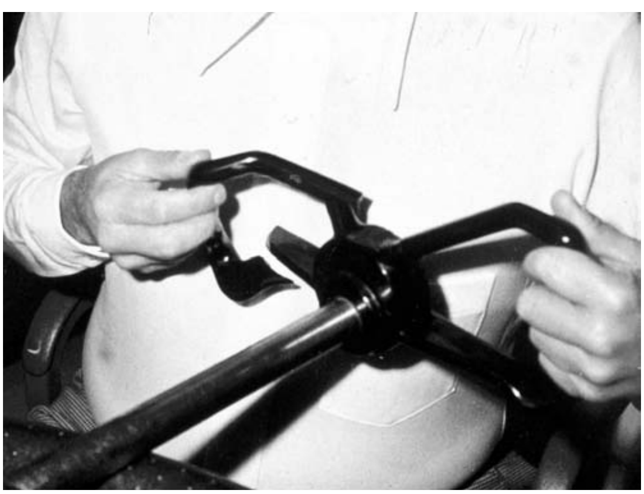


FIGURE 25-45 Investigator holds up broken passenger side broken control yoke. Notice the sharp edges and pointed fractures (photo courtesy of Civil Aerospace Medical Institute).

FIGURE 25-47 Investigators probe the fuselage; note the wing has been removed (photo courtesy of Civil Aerospace Medical Institute).

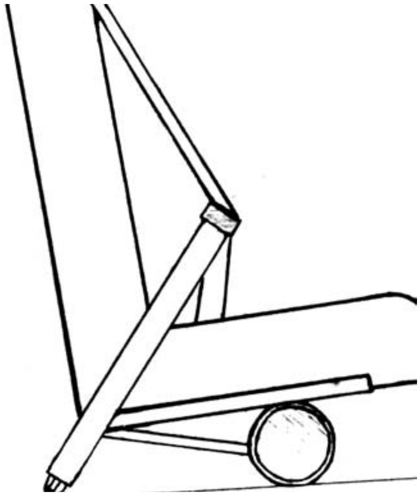


FIGURE 25-48 Drawing of the relationship of the seat to the circular main wing spar (photo courtesy of Civil Aerospace Medical Institute).

- Inadequate application of crew resource management principles
- Ineffectiveness of measures taken by the manufacturer in response to previous pressurization incidents in the particular type of aircraft

The AAIASB further concluded that the following factors could have contributed to the accident: omission of returning the cabin pressurization mode selector to the AUTO position after nonscheduled maintenance on the aircraft, lack of cabin crew procedures (at an international level) to address events involving loss of pressurization and continuation of the climb despite passenger oxygen masks deployment, and ineffectiveness of international aviation authorities to enforce implementation of actions plans resulting from deficiencies documented in audits (http://www.moi.gov.cy/moi/pio/pio.nsf/All/F15FBD7320037284C2257204002B6243/$file/FINAL%20REPORT%205B-DBY.pdf).

FIGURE 25-49 The bottom of the pilot's seat has been deformed by the main wing spar during the impact (photo courtesy of Civil Aerospace Medical Institute).

FIGURE 25-50 Radiograph showing vertebral fracture.

Chartered Learjet Fatal Accident—Four Passenger and Two Crew Deaths

In 1999, a Learjet Model 35 crashed near Aberdeen, South Dakota. The airplane departed Orlando, Florida, for Dallas, Texas. Radio contact with the flight was lost north of Gainesville, Florida, after ATC cleared the airplane to FL 390. Several U.S. Air Force and Air National Guard aircraft intercepted the airplane as it proceeded northwest bound. The military pilots in a position to observe the accident airplane at close range stated (in interviews or through radio transmissions) that the forward windshields of the Learjet seemed to be frosted or covered with condensation. The military pilots could not see into the cabin. They did not observe any structural anomaly or other unusual condition. The military pilots observed the airplane depart controlled flight and spiral to the ground, impacting an open field. All occupants onboard the airplane (the captain, first officer, and four passengers) were killed and the airplane was destroyed. The NTSB determined that the probable cause of this accident (**DCA00MA005**) was incapacitation of the flight crewmembers as a result of their failure to receive supplemental oxygen following a loss of cabin pressurization, for undetermined reasons (www.ntsb.gov/ntsb/brief.asp?ev_id=20001212X19931&key=1).

Decompression Illness

There have also been a few incidents and accidents related to decompression events, which can include air embolism and decompression sickness. The medical investigator will not usually have postmortem information to assist in these cases.

Case Summary

In 1994 during a nonscheduled 14 CFR Part 121 operation of a DC-8-61 to haul cargo, there was a serious injury due to decompression illness. At an *en route* stop, company maintenance personnel opened the forward overwing emergency exit to gain access to a navigation light that needed repair. The flight engineer said that during his preflight inspection, the emergency exit appeared to be in place, although he did not physically examine the exits or latches. Later, during climb out, the flight crew was unable to pressurize the airplane. Despite objections from the other crewmembers, the captain elected to proceed with the flight. The crew donned their oxygen masks and a climb was continued to a cruise altitude at FL 330. Shortly after level off, the captain became incapacitated from decompression illness. The first officer took command and the flight diverted for an emergency landing. After the flight, the emergency exit door was found lying inside the airplane. The NTSB determined the probable cause of this accident (**NYC94LA062**) to be the captain's improper decision to conduct flight at high altitude in an unpressurized airplane, which resulted in his incapacitation due to decompression illness. A factor related to the accident was that maintenance personnel failed to properly secure the emergency exit door after removing it to perform maintenance (www.ntsb.gov/ntsb/brief.asp?ev_id=20001206X00986&key=1).

Bird Strikes

Each year, many aircraft collide with birds in flight. These collisions are significant, especially when they involve larger birds, supersonic aircraft, or the ingestion of birds into an engine.

Determination of a bird strike as an event is seldom difficult if investigators examine the wreckage carefully. Even in the most severe cases, they can find remnants of the bird. An ornithologist, on examining the feathers, bones, or other fragments of a bird, can often determine the species and sex and estimate its age and weight. Laboratory personnel can examine fragments of tissue microscopically for nucleated erythrocytes and can perform other serologic tests.

Weather

Turbulence, thunderstorms, and temperature extremes are examples of weather conditions that can influence the course of events in an accident. Turbulent weather conditions can produce in-flight breakup of the aircraft. If some of the occupants are thrown from the aircraft as a result, as in the case of the Comet disasters, they will have different injury patterns, due to falling from altitude, from those who remained inside the aircraft.

Thunderstorms are a source of extreme turbulence, hail, and electrical activity. The cold temperatures at altitude and the lifting energy and moisture of thunderstorms combine to create hailstones up to several inches in diameter. These hailstones can damage lifting surfaces, cause engines to fail, and break windscreens. They may also be responsible for some abrasions and contusions in crewmembers after ejection in or near a thunderstorm. The effects of striking these hailstones is not as serious as the injuries inflicted on the crewmembers by the same extreme turbulent force that hurls hailstones thousands of feet in the air (Figure 25-51) (45).

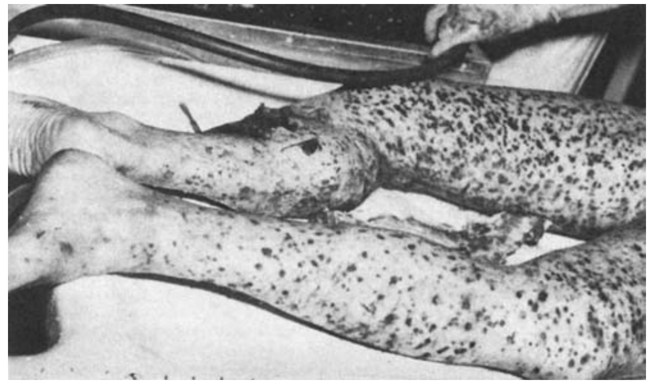


FIGURE 25-51 Injuries resulting from impact with hailstones after ejection in a thunderstorm (photo courtesy of Armed Forces Institute of Pathology).

Many persons on the ground have died after being struck by lightning, but few similar deaths have occurred in occupants of aircraft. Lightning has injured pilots. The electrical discharge passes primarily along the surface rather than through the center of a conductor. This "skin effect" diverts the electrical charge over the surface of the aircraft and protects the occupants except in a very few cases. Deaths have occurred in occupants of small planes and gliders, especially fabric-covered craft, which have passed directly in the path of a lightning discharge. Pinpoint burns of entry and exit, an arborization pattern of branching cutaneous erythema, and deposits from the arcing of electrical discharge along zippers and other metal objects among personal effects are evidence of a lightning strike.

The turbulence encountered may make spatial disorientation more likely due to increased difficulty maintaining a cockpit instrument scan during instrument flying conditions.

In February of 2007 in Australia, a German champion paraglider, Ewa Wisnierska aged 35, inadvertently ascended above 32,000 ft from a combination of vertical winds as two thunderstorm cells combined. She carried GPS and radio telemetry equipment so her ground crew could track her ascent and position even after she lost consciousness in the climb. She ascended from 2,500 to 32,612 ft in approximately 15 minutes. She regained consciousness after 30 minutes and at 1,640 ft was able to descend and land with frostbite injuries. Another competitor from China, He Zhongpin, aged 42 was also caught up in the storm but was killed by lightning.

Fire

In-flight fires, impact flash fires, and postcrash fires produce characteristic patterns. In-flight fires produce streaming patterns of soot deposition along the aircraft structures, usually seen best on aircraft surfaces rather than in the bodies of the victims. Postcrash fires may show a more vertical soot or heat damage pattern on aircraft structures. Flash fires, as from the fireball of ignited fuel at impact, produce first- and second-degree burns of unprotected skin surfaces. The interpretation of injury patterns in the case of a postcrash fire is much more difficult.

Burn fatalities occur when occupants have insufficient time to escape because of the rapid onset and propagation of fire, when incapacitating injuries prevent them from exiting the aircraft, when exits are jammed or obstructed, when personal protective equipment is inadequate, or when rescue and fire-suppression efforts are ineffective. The investigator must answer the following key questions:

1. Was the victim alive at the time of impact?
2. Was the victim incapacitated by preexisting disease, medications, toxic gases, or fire injury before impact?
3. Were the burns received postmortem? That is, were fatal injuries sustained at impact, with the burns occurring after death?
4. Did death occur because the victim was unable to exit the aircraft because of injury, toxic gas, smoke, or problems with emergency egress systems before being overcome by smoke and fire?

The most difficult determination is whether burn injuries occurred after death, yet the answer to this question is often the most important. Whether the burns resulting from the postcrash fire, or the injuries inflicted by the impact were more responsible for the victim's death, influences whether the investigator recommends improvements of egress systems and fire prevention, or of seats, restraint systems, and structural design.

The occurrence of burn injuries in U.S. Air Force aircraft accident victims increased from 27.4% to 40.2% from 1953 to 1967, and injuries from fire as the primary cause of death increased from 6.7% to 17.0% (49). Burns as the primary cause of death in U.S. Army aircraft victims also increased, from approximately 25% in 1957 to more than 40% in 1969, but the installation of a crashworthy fuel system on board Army UH-1 helicopters has virtually eliminated burn injuries as a cause of death in crashes of these helicopters. This is a dramatic illustration of the importance of the correct interpretation of whether burns occurred before or after death.

Laboratory determination of lactic acid levels in the brain, and more importantly of blood carboxyhemoglobin saturation and blood CN levels, may be of value in determining whether a crash victim was alive during the postcrash fire. The pathologist may also examine the respiratory system grossly for soot deposits and microscopically for a conclusive histologic response to combustion products of the fire.

Inexperienced investigators often conclude that fire-related postmortem artifactual changes were antemortem injuries. Heat-induced muscle contraction causes the body to assume a pugilistic attitude, as if the victim was protecting himself from the fire. The strongest muscle groups prevail, resulting in flexion of the hips, knees, and elbows but hyperextension of the neck. These heat contractions of muscles are frequently strong enough to produce bone fractures at the muscle attachment points. Rectangular bone fragments are characteristic in heat fractures of long bones.

Increased intracranial steam pressure that results from heating of the skull in a fire may produce blowout fractures that appear similar to an impact injury. Finding bone fragments within the cranial cavity may help distinguish these fractures. Heating of the skull may also force blood into the extradural space, creating the appearance of extradural hemorrhage. Exposure of the skin to gasoline or other aviation fuels produces epidermolysis, skin bullae, erythema, and the artifactual appearance of burn injury.

The investigator can usually relate the cutaneous burn pattern to protective equipment or to specific agents. Location of flare guns and oxygen bottles may provide clues to the cause of localized, severe burns. Extra thickness of clothing, such as pockets, belts, and waistbands, provide extra protection from burns.

Water

Postcrash survival in water is particularly hazardous. In this regard, rotorcraft ditchings are associated with a great likelihood of the downed aircraft inverting shortly after contacting the water, due to the high center of gravity with the engines, transmission, and rotors being located high on the fuselage. This rapid inversion places the occupants upside down and immersed in the water, which adds to the difficulty of escaping the aircraft. Drowning is a frequent cause of death after an aircraft crashes into water, but the exact frequency is difficult to estimate. No single autopsy finding or laboratory test is pathognomonic of drowning; the investigator must consider many factors before reaching this diagnosis, largely by excluding other diagnoses. Nevertheless, the correct determination of whether death occurred from drowning or from impact injuries is important.

A few of the external autopsy findings associated with drowning are a mushroom of froth in the nose and mouth and, occasionally, petechial hemorrhages beneath the conjunctiva. Prolonged exposure produces wrinkling of skin, so-called washerwoman's skin, but this finding may occur after death and is not an indicator of drowning. Internal findings include dilated blood vessels engorged with dark red blood that does not clot, congested lungs with petechial hemorrhages, and hemorrhage into the temporal bones. Microscopic examination may detect diatoms in blood or tissues, but this finding is of little value without comparison with samples of the water from the crash site. Laboratory tests to compare the concentrations of various electrolytes in the blood from the left and right sides of the heart, and to determine lactic acid concentration in the brain, may be helpful (these tests are discussed in the sections **Blood Electrolytes** and **Brain Lactic Acid**).

PREEXISTING DISEASES

Pilots are required to maintain a medical certificate in addition to their pilot certificate; this involves periodic health assessments by a designated aeromedical examiner (see Chapter 11). The time interval between the formal examinations to apply for medical certification may be as short as 6 months or as long as 5 years. Medical assessments for various conditions or combinations of medical conditions may be requested at more frequent intervals as necessary to help guide certification decisions. As an example, blood glucose values for insulin-requiring pilots during flight can be on an hourly basis. Pilots of ultralight aircraft, gliders, and balloons have a self-reporting medical status. Pilots are continuously screened out for various disqualifying conditions or medication use. One study of the longevity of airline pilots using life table analysis at CAMI indicated that those pilots, on average, live longer after retirement than the general population. In general, pilot health is excellent because they wish to maintain their livelihood. Pilots do occasionally have medically related incapacitations in the cockpit, and it is for this reason that airlines conduct incapacitation-training scenarios. The literature contains reports of almost every imaginable disease process—including a congenital anomaly, cardiovascular disease (CVD), neoplasm, and infection—causing a crash; however, the selection criteria, physical standards, and frequent medical supervision of flight crews probably detect most preexisting disease before an acute catastrophic health condition occurs in flight. The accident investigator is more likely to encounter what most people consider minor disease processes, which may nevertheless be a factor in the accident sequence. The exception to this would be something serious such as silent coronary artery ischemia, which might remain undetected, especially in a younger pilot. In accident investigation, it is easier to document preexisting illness in air carrier operations due to added surveillance available in commercial flight decks and with the increased frequency of medical examinations and pilot proficiency checks. In recent decades, no airline accident has been attributed to disease. This is so because of the additional flight crewmembers on the flight deck and pilot incapacitation response training, and is documented by the presence of the CVR, the FDR, and possibly witnesses. In general aviation, however, there is often a scarcity of facts available to help guide the investigator in pursuing possible pilot incapacity or impairment as reasons for the accident. Therefore, postmortem examinations and toxicologic testing assume a very important role in searching for preexisting illness and for signs that illness may have precipitated the accident.

Did the disease cause the accident? The investigator will want to answer this question. Minor diseases, especially self-imposed stresses such as self-medication and fatigue, play a much greater role in causing accidents than most investigators have been willing to accept, and diseases that remain undisclosed at autopsy, such as epilepsy and cardiac arrhythmias, are of particular concern.

Detection of Preexisting Disease

After an accident, the first suspicion that preexisting disease may be present often comes from examining the medical records of the crew. Examination of their medical records early in the course of the accident investigation, certainly before the autopsy examination, can be a valuable time-saving step. In fact, the documentation of some preexisting conditions may require special techniques that the pathologist would not usually use, and if the medical records are not available until after the autopsy has been completed, the pathologist may be unable to identify a suspected preexisting disease.

A careful, complete autopsy usually discloses any preexisting injury or disease that is present, but even when the cause of death appears obvious, the investigator must be alert for underlying preexisting conditions. Although the pathologist can easily detect most preexisting diseases by gross examination of the tissues, the discovery or confirmation of some conditions requires toxicologic or microscopic examination. Histologic examination may be the only way to determine whether a contusion occurred days or weeks before the crash, during the crash, or after death. Pilot incapacitation has resulted from acute appendicitis, acute glaucoma, and Ménière's disease, but the investigator may not detect these conditions until he or she examines the histologic sections. If a pilot is incapacitated from a cardiac condition (infarction or dysrythmia), the resulting impact from inability to control the aircraft may mask the actual cause of the incapacitation unless there are surviving witnesses or air traffic controller communications available.

Significance of Preexisting Disease

The presence of preexisting injuries or disease can be a source of confusion. Distinguishing acute from chronic disease processes is not always easy, and even a preexisting, long-standing disease process can precipitate an acute catastrophic event. Distinguishing between those disease processes that might have contributed to the accident and those that were entirely unrelated to the cause of the crash is especially important but often very difficult. The mere presence of preexisting disease does not mean that it was a factor in causing the accident. Investigators may have a difficult time proving that it was a cause, but the preexisting disease may have been a contributing factor in causing a "pilot error" or "cause-undetermined" mishap.

The most significant disease is one that goes undetected in the screening process, contributes to the cause of an accident, and remains undetected during the investigation process. Careful scientific analysis is necessary to find any previous disease and to distinguish merely incidental pathologic findings from disease entities causing disability of crewmembers. Development of markers for myocardial infarction (MI) that would remain detectable postmortem is very much needed in accident investigation.

Neurologic Disease

Review of aircraft accident investigation data has disclosed few cases attributed to neurologic disease. The AFIP files contain a few aircraft accident cases involving crewmembers with neurologic disorders such as Parkinson's disease, Ménière's disease, and space-occupying intracranial lesions, including pituitary adenomas and colloid cyst of the third ventricle.

Well-documented cases in which investigators have shown epilepsy to be the cause of an aircraft accident are extremely rare but have been documented by the Medical Aircraft Accident Research Team at CAMI. Incapacitation of professional pilots due to epilepsy has occurred in flight and is followed by the CAMI team in a database of pilot incapacitations. This database contains all U.S. airline pilot in-flight incapacitations and impairments with somewhat varying numbers of general aviation events (http://www.faa.gov/education_research/research/med_humanfacs/aeromedical/aircraftaccident/).

The U.S. Air Force reported that 33% of 30 asymptomatic crewmembers with abnormal electroencephalographic findings were involved in accidents or incidents or had a neurologically related clinical event. It also reported that 13% died in accidents.

Cardiovascular Disease

CVD in crewmembers is part of the normal aging process and is of major concern as a cause of fatal incapacitation and accidents. It is prevalent, even in the relatively young military population. Pettyjohn and McMeekin (50) reported the AFIP's experience in reviewing autopsies of 6,500 aircraft accident victims. Of these fatalities, 816 (13%) had preexisting, nontraumatic heart disease.

The literature contains numerous reports of pilots having heart attacks at the controls, but few crashes have occurred. The U.S. Air Force concluded that in-flight MI is a rare event after it found only two cases of confirmed and five cases of suspected in-flight MI between 1962 and 1972. One international airline reported that only 17 of its pilots experienced health-related incidents between 1948 and 1972. Of the 13 incidents related to the cardiovascular system, only 11 were coronary infarcts, and no crashes occurred (51).

This low incidence is consistent with the experience of other airlines, and the statistics may be quite accurate, considering that most airlines have cockpit voice recorders and FDRs. At CAMI in-flight incapacitation of commercial flight operations are tracked. Although there have been cardiac-related incapacitations, such as atrial fibrillation, none has resulted in an accident. Professional pilots also train to handle pilot incapacitation in multicrew cockpits. Nevertheless, the general flying public worries about the health of airline pilots who literally hold the passengers' lives in their hands. Most investigators reflect this concern.

Histologic examination of the heart is particularly helpful. The shearing forces of trauma (Figure 25-52) and the coagulating effect of heat from fire may create lesions that appear grossly like coronary thrombosis. Careful microscopic examination of multiple sections may reveal the foci of myocarditis. Because these foci also occur in healthy people who die, they may be simply minor injury patterns representing the normal wear and tear of repetitive cardiac contractions. The investigator should evaluate the finding of myocarditis carefully, with full consideration of all the facts associated with the accident.

The pathologist may occasionally encounter MI associated with an aircraft accident, but trying to find evidence to prove that early MI, especially in the absence of coronary

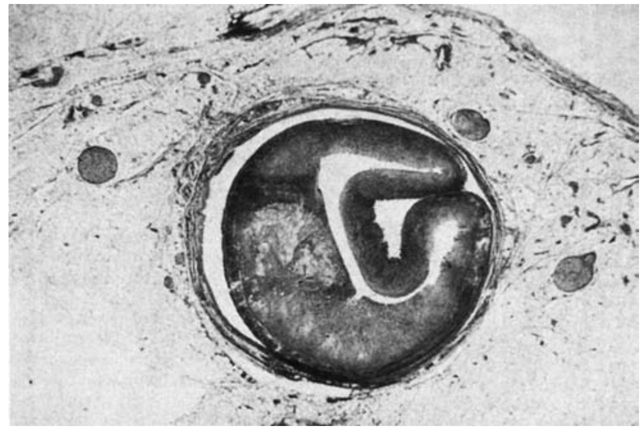


FIGURE 25-52 Traumatic force separated the intima and media from the less dense adventitia, creating the artifactual appearance of coronary occlusion (photo courtesy of Armed Forces Institute of Pathology).

thrombosis, is especially frustrating. Although histologic examination may be helpful in estimating when the infarction occurred in relation to the time of death, the most optimistic histochemical tests purport to detect myocardial ischemia only as early as 30 minutes after onset, and this is of no value when a crash precipitously follows the acute myocardial event. Some research regarding postmortem determination of cardiac death has been conducted in Japan and South America, specifically relating to cardiac muscle components such as troponin in pericardial sac fluid. However, more research in this area is needed. Gene expression research may hold some promise for postmortem analysis in aircraft accident investigation. At least one recent article has highlighted an artifactual histologic finding due to impact forces (52).

Incidental Cardiac Findings

Incidental findings or "necropsy surprises" in routine autopsies have been used in epidemiologic studies to determine the prevalence of important chronic conditions such as biliary tract and abdominal aortic diseases, as well as a variety of common forms of cancer. One advantage of this approach is that it provides a quasirandom sample of the general population which provides an indication of the prevalence of these conditions (53).

In aviation medicine, autopsy findings provide an effective epidemiologic tool in helping to (a) identify unsuspected or "surprising" diagnosis in a significant number of cases, and (b) uncover hidden preexisting conditions which the pilot may have been aware of but did not discuss with his/her AME.

Although medical incapacitations caused by heart attack in commercial flights are rare, CVD continues to be critical in aviation safety because there may not be prior indications of the disease. Although the first reported case of a deadly heart attack during flight in a 35-year-old military pilot was published seven decades ago (54), only eight studies on postmortem findings of cardiovascular abnormalities in both military and civilian aircrew have been published since

1959. Over the last two and half decades, three studies of U.S. civilian pilots involved in fatal accidents have been conducted using data from the CAMI.

In a recent study aimed to determine the prevalence of cardiovascular abnormalities in U.S. Civil Aviation Pilots Involved in Fatal Accidents (55), the NTSB database search revealed that between January 1995 and December 2000, a total of 2,292 fatal accidents occurred with 2,123 pilot fatalities. In addition, a total of 871 autopsy reports from the CAMI Autopsy Database during the same period were reviewed for the presence of incidental cardiac findings (ICFs) in pilots medically certified by the FAA.

ICFs were found in 375 pilots (out of 871), with a prevalence of 43%. Results also suggested that an increase in age is directly related to an increase in the frequency of ICFs, particularly in pilots older than 40 years. In addition, 54.2% of the pilots with ICFs ($n = 367$) were classified as overweight [body mass index (BMI) of 25–29.9], followed by 28.1% as normal weight (BMI of 18.5–24.9) and 17.4% as obese (BMI $\geqslant$ 30). As related to Type of Operations and Medical Class, 90.4% of the pilots were general aviation (Part 91) certified pilots, followed by Air Taxi (Part 135) and Agricultural (Part 137). Most of the pilots held a third-class medical certificate (46.9%), followed by a second class (37.6%) and first class (9.1%). Remarkably, 6.1% of the pilots with ICFs were flying "illegally"; because they had no medical certificate (2.6%), their medical certificate was denied (2.1%), or it was pending/deferred (0.5%).

From a total number of 503 cardiovascular abnormalities found in these pilots, coronary artery disease was the most common (61%), followed by aortic atherosclerosis (21%), ventricular hypertrophy (6%), MI (3%), myocardial fibrosis (3%), and cardiomegaly (3%). As related to CAD severity, mild, moderate, and severe levels of CAD were more common in the left coronary artery (LCA) and left anterior descending (LAD), followed by right coronary artery (RCA) and circumflex artery.

Myocardial Infarction Reported on Autopsies

MIs were found in 15 of the 375 autopsied pilots with ICFs (4%). Aeromedical Certificate Division (AMCD) had recorded the pilot's cardiovascular preexisting condition in approximately one third of these cases (33%).

In addition, the most common cardiovascular abnormalities found in patients with MI were (a) CAD (60% or 9 of 15 pilots), (b) aortic atherosclerosis and bypass surgery (27% respectively or 4 of 15 pilots), (c) myocardial fibrosis (13% or 2 of 15 pilots), and (d) cardiomegaly (6% or 1of 15 pilots).

"Acute" MI was reported in 2 of the 15 pilots with MIs (13%). One of these two cases was cited by the NTSB as medical incapacitation in-flight due to a heart attack. Another case was reported as myocarditis in the right ventricle, with no indication by the NTSB as related to the cause of the accident.

Comparison of ICF prevalence with previous studies has proved to be very challenging because (a) autopsy rates are different in terms of the number of fatalities in aircraft accidents versus the number of autopsies performed, (b) methodologies are different in terms of the type of operations (military versus civilian), (c) role of the occupant (pilot/passenger), and (d) lack of a standardized classification of CAD severity (grading level) by medical examiners/pathologists.

Consistent with the literature, the prevalence of CVD increases with age, particularly in pilots older than 40 years. An increased incidence of incapacitation events with age is also seen. The proportion of pilots that have a mishap in any given year increases with age; note that this is not a rate, but has been consistent for many years. The number of pilots involved in a mishap compared to the number of all pilots for that age increases as age increases. Cases with evidence of acute MI need further analysis to rule out a sudden medical incapacitation as the cause of the accident. Any cardiac risk detection program in pilots should be aimed primarily at general aviation pilots. Finally, ICFs studies in autopsied pilots provides additional information to support the use of autopsy data for decision making, to improve accident analysis and to confirm if coronary heart disease trends in pilots are changing.

Case Summaries

Supraventricular Tachycardia

A young pilot engaged in aerobatic flight near Goldsby, Oklahoma, in 1976, died on impact with the ground in a loss of controlled flight, described by witnesses as if the plane, which had been doing loops, just stopped flying and descended smoothly into the ground (FTW76AF106). As the investigation proceeded, assisted by personnel from CAMI, the medical history of the pilot included episodes of syncope associated with a "racing heart." The pilot did not tell his treating physician that he was a pilot, and did not tell his AME about his heart condition. His underlying condition, Wolfe-Parkinson-White syndrome, was unknown to the certifying authorities as he was not yet old enough to have been required to submit an electrocardiogram (ECG) report. While in 1976, his condition, which was symptomatic and did result in syncope on more than one occasion, might have led to his grounding, the passage of time and the progress in treatment options would have eventually led to a situation where his underlying dysrhythmia could have been treated by catheter ablation of his aberrant conductive pathway(s), and he could well have continued flying again, even as a commercial pilot. His nondisclosure of his medical condition from the medical certification process resulted in his untimely death.

During an airshow, a fatal accident occurred when the very experienced pilot sustained an incapacitation shortly after a barrel roll preceding a wing-walker act (NYC93FA127). Review of videotape of the accident showed that the pilot was likely incapacitated because at least one opportunity to recover the aircraft was not acted upon. The wing-walker passenger, his daughter, was not a pilot. The autopsy findings were that the heart is normal size and the coronary arteries follow their usual distribution;

however, there is severe atherosclerosis of the proximal LAD artery and its branches with up to 90% to 95% focal closure. The myocardium reveals an old MI scar of the anterior septum in a subendocardial location. Microscopic sections of the heart reveal well-developed mature scar tissue. The coronary artery reveals essentially complete occlusion by mature atherosclerosis with focal calcification. Several experts from CAMI, AFIP, and the International Council of Air Shows, reviewed the circumstances to assist the NTSB in their determination of pilot incapacitation due to cardiac causes (DeJohn, *personal communication*, 1973).

Sarcoidosis

Sarcoidosis is a relatively common disease that may cause sudden incapacitation and even death, but the incidence of clinical manifestations is low. Balfour (56) reported 16 cases of "sarcoid-like granulomas" in autopsies of 852 crewmembers, although the reported incidence of clinical sarcoidosis in the United Kingdom is only approximately 3/100,000 individuals/yr. Only one of his subjects had cardiac involvement. Pettyjohn et al. (57) reported on 36 U.S. military crewmembers with clinical sarcoidosis. Thirty-three percent had evidence of cardiac involvement; 4 of the 36 had significant cardiac abnormalities, and 8 had electrocardiographic abnormalities. These findings are higher than the reported incidence of 13% to 20% in the general population.

Although no evidence clearly establishes that sarcoidosis causes aircraft accidents or that aviation duties make crewmembers more susceptible than others to the lesions of sarcoid, investigators may be underestimating the importance of sarcoidosis as a significant etiologic factor in aircraft accidents. Figure 25-53 illustrates the case of a pilot with severe sarcoidosis with multiple organ involvement, including the heart. Investigators concluded that the cardiac involvement probably resulted in incapacitation of the pilot. The injury pattern observed in the passenger of this small aircraft suggested that the passenger and not the pilot was operating the controls at the time of the crash.

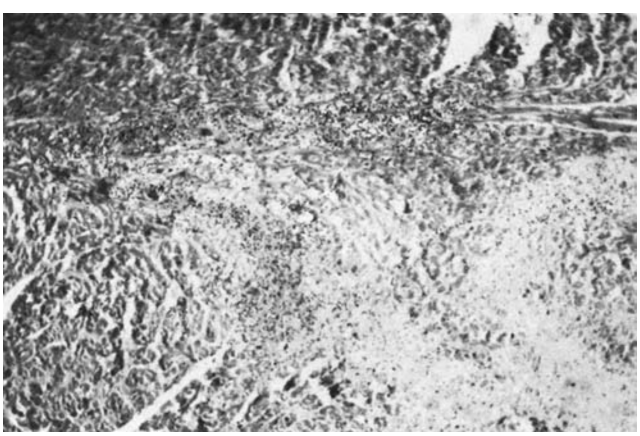


FIGURE 25-53 Sarcoid granulomas in the heart (photo courtesy of Armed Forces Institute of Pathology).

FIGURE 25-54 Carcinoma of the thyroid (photo courtesy of Armed Forces Institute of Pathology).

Infections

Infections in the upper respiratory tract, especially those involving the sinuses, occur frequently in crewmembers as a result of repeated barotrauma from ascending and descending during flight. These infections may lead to ear involvement, disturbances of equilibrium, and a subsequent accident. The frequency of "nonspecific but definitely abnormal" respiratory tracts in 31 pilots involved in unexplained crashes of single-seat, high-performance aircraft impressed Mason (58), and he suggested that these infections may cause more crashes than investigators have been willing to acknowledge. These nonspecific changes may have been a marker for mild unreported illnesses that may have had negative performance effects such as fatigue, or may have been accompanied by the use of unreported medications. Note the high incidence of the use of over-the-counter drugs in Table 25-6.

Tumors

Tumors can be a cause of sudden incapacitation, especially primary or metastatic lesions of the brain, where seizure, cerebral vascular accident, or sudden cognitive decline could occur. The AFIP reported reviewing 6,405 aircraft accident fatalities and finding 90 unsuspected tumors (Figure 25-54). This number is impressive considering the following factors:

1. The tumors occurred in crewmembers who were required to have a physical examination at least once each year.
2. The pathologists were able to obtain tissue for microscopic examination in less than 50% of the cases.
3. Microscopic examination was present in less than 30% of the cases.
4. The microscopic examination in other cases was superficial.

Alcohol, Self-Medication, and Substance Abuse

The ingestion of alcohol, or prescribed or illicit drugs, self-medication with over-the-counter drugs, or even the excessive consumption of various food products can lead to impaired function of crewmembers. Alternative medications have been deemed by the U.S. Food and Drug Administration to be food supplements and not drugs, except for compounds such as ephedra, for which they are considering regulation. Pilots may consume alternative medications thinking that they are not prohibited from use while on piloting duties and may experience the ill effects of drug interactions, or side effects from these multicompounded products. Pilots and investigators should also remember that the underlying conditions for which the pilots are using the alternative medications might themselves cause problems in flight, leading to an accident or incident even if the alternative medication is safe.

Aircraft accident toxicology laboratories find that crewmembers ingest ethyl alcohol more than any other toxic substance. Of the unusually large number of aircraft accident victims testing positive for the presence of alcohol before about 1965, many were probably positive as a result of postmortem putrefaction or inadequate laboratory methods; however, even after the introduction of better collection and preservation techniques and with superior analytical processes such as gas chromatography and headspace gas chromatography (gold standard), the incidence remains high enough to complicate accident investigations (59). Many positive results are still attributable to postmortem decomposition with the resultant bacterial production of alcohol. In a 1989 to 1990 review of toxicology findings of 975 aviation accident cases, 79 (8%) of the cases had a blood alcohol level of 0.04% (40 mg/dL). Looking at ethanol distributions in urine, vitreous humor, blood, and tissue, it could be determined that 21 of the 79 cases (27%) were from postmortem alcohol production, and that 22 of the 79 cases (28%) were due to ingestion of ethanol. It is important to note that the authors could not make a determination of antemortem consumption or postmortem production of ethanol in 36 of the 79 cases (45%). They also had two cases of postmortem production where they found more than 0.15% (150 mg/dL). They found that 22 of 975 (2.3%) cases contained sufficient evidence of antemortem consumption. The paper does not say how many of the accidents where antemortem consumption was verified were determined by the NTSB to be due to alcohol. They also conclude that the presence or absence of other volatiles does not establish postmortem ethanol production (60). A useful guide to aviation accident investigation involving alcohol can be found at the Australian Transport Safety Bureau website (http://www.atsb.gov.au/publications/2005/pdf/Measured_alcohol_lev.pdf).

The U.S. Air Force reported that the ingestion of ethyl alcohol was associated with 28 of approximately 4,200 aircraft accidents from 1962 through 1974 (61). The FAA reported that alcohol levels in 28 (13.9%) of 202 general aviation accidents were greater than 0.05% (50 mg/100 g) (62). Compare this with the more recent review of drugs and alcohol in civil aviation in the study described in the subsequent text covering 1994 to 1998 (63). General aviation accidents in the United Kingdom during a similar period of a study, 1964 through 1973, resulted in positive alcohol determinations in 34 of 102 pilots; however, only 12 accidents (11.6%) involved alcohol ingestion before flight. The 1983 AFIP toxicologic findings of 2,326 occupants of aircraft mishaps are summarized in Table 25-5.

TABLE 25-5

Drugs Found on Examination of 2,326 Occupants of Aircraft Mishaps in 1983

Substance	*No. of Occupants*
Salicylates	109
Acetaminophen	61
Cannabinoids	54
Ethanol	51
Opiates	18
Chloroquine	6
Barbiturates	5
Amphetamines	2
Benzodiazepines	1
Chlorpheniramine	1
Cocaine	1
Diphenhydramine	1
Furosemide	1
Hydrochlorothiazide	1
Lidocaine	1
Phencyclidine	1
Total	314

The CAMI toxicology laboratory found the substances listed in Table 25-6 when they examined 1,683 pilots from predominantly general aviation operations involved in aircraft mishaps from 1994 to 1998 (63). Rescue personnel may have used lidocaine, procainamide, and possibly morphine in resuscitation efforts; other agents, such as marijuana and cocaine, would certainly be associated with drug abuse. Of the 1,683 pilots, 89 (5%) tested positive for controlled dangerous substances schedules I and II, which represented a 25% increase over the 1989 to 1993 period. In 49 pilots (3%), controlled dangerous substances schedules III through V were found, representing an increase of 48% over the previous 5 years. Prescription drugs were found in 240 (14%) of the pilots analyzed, which represented a 58% increase. Over-the-counter drugs were found in 301 (18%) of the pilots analyzed, which constituted a 37% increase over the prior study. Alcohol at or above 0.04% (40 mg/dL) was found in 124 pilots (7%) and represents both known consumption and unknown or possible consumption combined with postmortem production of alcohol. The range of alcohol-positive results seems to remain relatively stable from year to year at 4% to 9%. The presence of drugs such as chloroquine probably represents cases of approved usage. Although the use of drugs such as salicylates or acetaminophen may have been approved in some instances, most cases involved the self-medication of

TABLE 25-6

Drugs Found in 1,683 Pilots Involved in Civil Aviation Accident Cases between 1994 and 1998

Drug Schedule	*Drug*	*Total Pilots*
Controlled dangerous substances schedules I and II	Amphetamine/methamphetamine	11
	Barbiturates	9
	Cocaine	13
	Codeine/morphine	17
	Marijuana	43
	Methaqualone	0
	Phencyclidine (PCP)	0
	Synthetic opiates	10
Controlled dangerous substances schedules III–V	Benzodiazepines	33
	Fenfluramine	5
	Pentazocine	1
	Phendimetrazine	0
	Phentermine	7
	Propoxyphene/norpropoxyphene	10
Prescription medications	Amitriptyline/nortriptyline	1
	Atenolol	13
	Azacylonol	5
	Brompheniramine	7
	Carbamazepine	1
	Cimetidine	6
	Diltiazem	10
	Diphenhydramine	54
	Fluoxetine/norfluoxetine	18
	Gemfibrozil	1
	Ibuprofen	9
	Imipramine/desimpraamine	5
	Ketamine	1
	Lidocaine	32
	Metoprolol	5
	Minoxidil	1
	N-acetylprocainamide/procainamide	1
	Naproxen	7
	Nizatidine	2
	Phenytoin	9
	Promethazine	3
	Propranolol	3
	Sertraline/desmethylsertraline	5
	Sildenafil/sildenafil metabolite	1
	Theophylline	4
	Triamterene	7
	Verapamil/norverapamil	18
Over-the-counter medications	Acetaminophen	81
	Chlorpheniramine/norchlorpheniramine	44
	Dextromethorphan	18
	Dextrophan/nordextrophan	8
	Doxylamine	15
	Ephedrine	47
	Guaiphenesin	1
	L-methamphetamine	1
	Meclizine	1
	Melatonin	1
	Methylephedrine	1
	Naphazoline	1
	Oxymetazoline	2
	Phenylpropanolamine	82
	Pseudoephedrine	84
	Quinine	19
	Salicylates	114

an underlying condition that would have been disqualifying for flight duties. The presence of ephedrine, which has a low threshold for toxicity, probably represents the use of alternative medication products containing the ephedra root. Pharmaceutical products usually contain pseudoephedrine due to its enhanced therapeutic to toxicity ratio. Some of the increase in detection rates may be due to improved toxicology methodologies, but the increasing use of medications in general aviation remains a potential detriment to safety improvements.

LABORATORY TESTS AND INTERPRETATION OF RESULTS

Many laboratory tests are available to assist the investigator, but the correct choice of the methods and careful interpretation of the results are important.

Serologic Studies

Serologic studies, such as the determination of blood type, are often useful in narrowing the possible identities of an unknown body. The investigator must exercise caution in the performance and interpretation of serologic studies, because numerous possibilities exist for error and for the introduction of artifacts.

Perhaps the simplest serologic test is the use of antihuman globulin (Coombs serum) to determine whether a tissue is human or nonhuman. Using proper techniques, this distinction can be made even on dried bones that are more than 100 years old. This test is of particular value in cases in which a long time has lapsed from the occurrence of the disaster to the time of discovery and in which the possibility exists of commingling with animal remains. The technique is also useful in the investigation of aircraft accidents in which a bird strike is suspected.

The detection of A and B blood group substances in blood, tissue, or fluids is helpful in determining the blood type of the deceased. Dried blood in these tests produces the best results, which is advantageous because the investigator cannot always draw blood immediately after death and separate serum and cells. Comparing blood group substances, A and B seem more stable than the others after death. Many other blood group substances deteriorate rapidly, and even A and B substances may yield erratic results upon laboratory testing.

Positive benzidine, orthotoluidine, or phenolphthalein test results may indicate the presence of blood, but interference by many plant, chemical, and other animal sources of peroxidase activity may result in false-positive results. The determination of hemochromogen crystals by procedures such as the Takayama test or of hemin crystals by the Teichmann test also indicates that blood is present.

If blood is present, the investigator may use absorption-inhibition, absorption-elution, Lattes crust, or Howard-Martin cellulose acetate sheet tests to determine the blood type. Absorption-elution tests are sensitive and accurate, and only small amounts of dried material are needed. Direct agglutination techniques using known antisera give erroneous results because the blood cells are damaged in dried stains, and postmortem changes introduce numerous artifacts.

Several techniques allow the determination of the species of origin of a bloodstain or tissue. The interfacial ring-precipitin test, the Ouchterlony gel double-diffusion test, and the antiglobulin-inhibition technique are three common methods using species-specific antisera.

Toxicologic Studies

Toxicologists have methods to detect many drugs and to determine the levels of substances that occur normally in human tissues. They are especially capable of performing these analyses on postmortem tissues and fluids that would be very difficult for one to perform reliably in the usual hospital laboratory. There is still necessary research in understanding postmortem artifacts and in finding postmortem indicators of antemortem conditions such as MI. In addition, more information on various compounds, such as the volume of distribution and partition coefficients, is useful to the investigator, who must often interpolate or extrapolate from tissue drug levels back to serum or whole blood levels to help determine the role of a particular substance in altering human performance. Sometimes the absence of a drug finding, in post–accident toxicology testing, is useful. Sudden discontinuation of a medication may provoke an in-flight incapacitation.

A thorough postmortem toxicology analysis can also be used to clear pilot reputations; it can show that despite rumors to the contrary, the pilot was free of medications or alcohol at the time of the accident.

Drugs and Volatile Substances

Many toxicology laboratories use solvent–solvent extraction followed by gas chromatographic and mass spectrographic examinations for drugs in the nonvolatile organic acid, basic, and neutral groups. Volatile substances (e.g., alcohol) can be detected by headspace gas chromatography. The investigator should remember that these procedures screen only for classes of compounds; many substances can be detected only by procedures that test for them specifically.

Blood Glucose

Hypoglycemia may be a factor in the cause of aircraft accidents, but the accurate determination of the glucose level in the blood of a fatally injured crewmember at the time of the crash is difficult. The cells continue metabolism for a short time after death, causing blood glucose to decrease to very low levels. Then, as tissue breakdown occurs, the blood glucose level becomes very elevated. Depending on where the blood is collected from, but especially if it is collected from the inferior vena cava, the glucose level may be greater than 1,000 mg/dL. Glucose levels in the vitreous of the eye do not change as rapidly, making the vitreous a good source of fluid for estimating the postmortem glucose level.

Rapid chilling further inhibits the postmortem decline in concentrations of vitreous humor glucose. It may be easier to show hyperglycemia in postmortem specimens than hypoglycemia (64). (http://www.faa.gov/library/reports/medical/oamtechreports/2000s/media/00_22.pdf). Glycosylated hemoglobin (HgA1c) may be further evidence of hyperglycemia in an aviation accident victim (http://www.hf.faa.gov/docs/508/docs/cami/0112.pdf)

Brain Lactic Acid

This has become a less definitive test according to current thinking. Historically Dominguez et al. (65) reported an association of brain lactic acid concentrations of greater than 200 mg/100 g with asphyxial deaths. The determination of the lactic concentration in the brain by ultraviolet spectroscopy requires approximately 500 mg of gray matter that is a very large sample. The myelinated white matter and peripheral nerves give unreliable results.

Finding elevated concentrations of lactic acid in the brain might be of interest in cases of drowning, death occurring in fires, and altitude hypoxia, but the mechanism that produces this elevation is not clear. Certainly, the most frequent cause of an elevated postmortem lactic acid level in the brain is resuscitation efforts with intravenous fluids.

Perhaps gene expression testing, if and when it becomes available in testing postmortem brain tissue, may supplant this older toxicologic assay.

Carbon Monoxide, Cyanide, and Other Combustion Products

Blood carboxyhemoglobin saturation gives an indication of the magnitude of antemortem exposure to carbon monoxide. More reliable laboratory methods and equipment, such as differential colorimetric spectroscopy and gas chromatography, now allow the accurate determination of carboxyhemoglobin saturations less than 1%, rather than the 10% level generally considered significant; however, a wise investigator will seek an explanation of even the lowest carboxyhemoglobin (COHg) saturations.

The ambient concentration of carbon monoxide in the breathed air and the duration of exposure determine the level of COHg saturation. Smokers seldom have COHg saturations greater than 10%, although higher levels may occur in cigar smokers. One crewmember who smoked more than two packs of cigarettes in less than 30 minutes *en route* to the hospital after a crash had a COHg saturation of 17%. Victims may breathe the products of a postcrash fire for more than 1 minute without reaching 20% COHg saturation and for more than 5 minutes without reaching 50% saturation. In rapid conflagration situations, victims who survived the impact forces may be found to have died in the postcrash fire before the COHg saturation reached even 10%. Therefore, the investigator should seek an explanation for even low COHg saturations. Low levels of COHg may cause passengers considerable distress and weakness increasing their difficulties of finding an exit in a smoke- and heat-filled cabin interior. Survivors of postcrash fire frequently report they felt weak even after only a few breaths of the toxic air. Postcrash fires or prolonged in-flight exposures of passengers to smoke and fumes can result in high levels of carboxyhemoglobin. In-flight exposures to combustion products for pilots usually do not get much above 40%, because at this level the pilot becomes incapable of continuing to control the aircraft, and if the aircraft is not on autopilot, a crash ensues shortly after this point. There will be no further opportunity to increase the carboxyhemoglobin levels unless there is a period after impact, in a postcrash fire, where the pilots survive for a period of time and continue to breathe the combustion products.

Carbon monoxide has a great affinity for hemoglobin and competes for its oxygen-carrying capacity. The reduced oxygen-carrying capacity of hemoglobin was generally considered to produce sufficient hypoxia to cause death in fire victims. This may still be the reason for these deaths, but it has been suggested that the true mechanism by which carbon monoxide causes deaths in fires is its effect on cellular respiration by binding of intracellular cytochrome a_3 in competition with oxygen. Therefore, the carbon monoxide dissolved in plasma, entering the cells, and binding cytochrome a_3 may be more significant than the limitation of the oxygen-carrying capacity of hemoglobin by carboxyhemoglobin. This would explain why some unburned victims die with relatively low carboxyhemoglobin concentrations and some survivors recover even after reaching carboxyhemoglobin saturations greater than 50%.

Many other products result from combustion, depending on the fuels and the composition of the atmosphere in which they burn. Many plastics, when burned, produce CN gas. CN is a potent enzyme poison but may not be more toxic than carbon monoxide in this regard. Other materials, such as electrical wiring, may produce halogenated hydrocarbon products, and laboratory measurements of chloride and fluoride may be helpful. There is an additive toxic effect from COHg and CN and levels of either alone that would not be expected to cause incapacitation or death, when combined do cause such problems for passengers. In an air carrier accident involving a collision between a landing Boeing B-737-300 aircraft, and a smaller commuter turboprop Fairchild SA-227 in position and hold at a runway–taxiway intersection, there was a secondary collision with a building and the rapid development of an oxygen-fed fire (**DCA91MA018A**). In Figure 25-55 there is a visible partial obstruction to the type II overwing emergency exit. The door plug was placed on the seat cushion and it is noteworthy that the seat back, which is normally purposefully fixed in the upright position in an exit row seat, is broken over the seat cushion with the door plug. On examination, the bolt securing the seat back had been broken by passenger action. The partial obstruction, of approximately a quarter to one third of the surface area of the exit, caused a slowing of passengers using the exit who approached the exit from the front of the aircraft. Figure 25-56 shows the assigned seating of the passengers who were unsuccessful in egressing the aircraft, and the positions where their bodies were recovered along with some

FIGURE 25-55 Type II overwing exit with partial obstruction to the exit from the door plug and the seat back position.

color-coding for the toxicology testing for COHg and CN. The delay in accessing the exit and the rapid development of a toxic cabin environment led to smoke inhalation being the cause of death for most of the fatalities in the B-737, and the bodies were found in their positions queuing for the exit. Most of the fatalities came from seats in front of the exit row, the flow from passengers coming from behind the exit row was less impeded, and due to the obstructions, it was easier to exit from the row behind the designated exit row, favoring those coming from the rear of the aircraft. The passengers are numbered and the astute reader will have noticed several unusual patterns of pre- and postcrash movement of some of the passengers that is always deserving of detailed survival factors investigation effort.

Blood Electrolytes

The comparison of electrolyte concentrations in blood from the left and right heart chambers as a diagnostic test for drowning is controversial. Theoretically, freshwater drowning dilutes the electrolytes in the left heart chambers, and saltwater drowning concentrates some of the electrolytes in the left heart chambers; postmortem changes increase the complexity of these interpretations.

The Gettler test relied on finding a difference in chloride concentration of 25 mg/dL between the left and right heart chambers. The interpretation of results is even more complicated when drowning occurs in brackish water, because the chloride concentration of the water may not be very different from the chloride concentration in the blood. The measurement of other electrolytes, such as magnesium, may be helpful in these cases. Collecting a sample of the water at the drowning site will allow the laboratory to select the electrolytes that might be useful in the comparison.

Artifact and Error

An interesting paper published in 2006 by Johan Duflou et al. (52) highlights a histological artifact from severe trauma

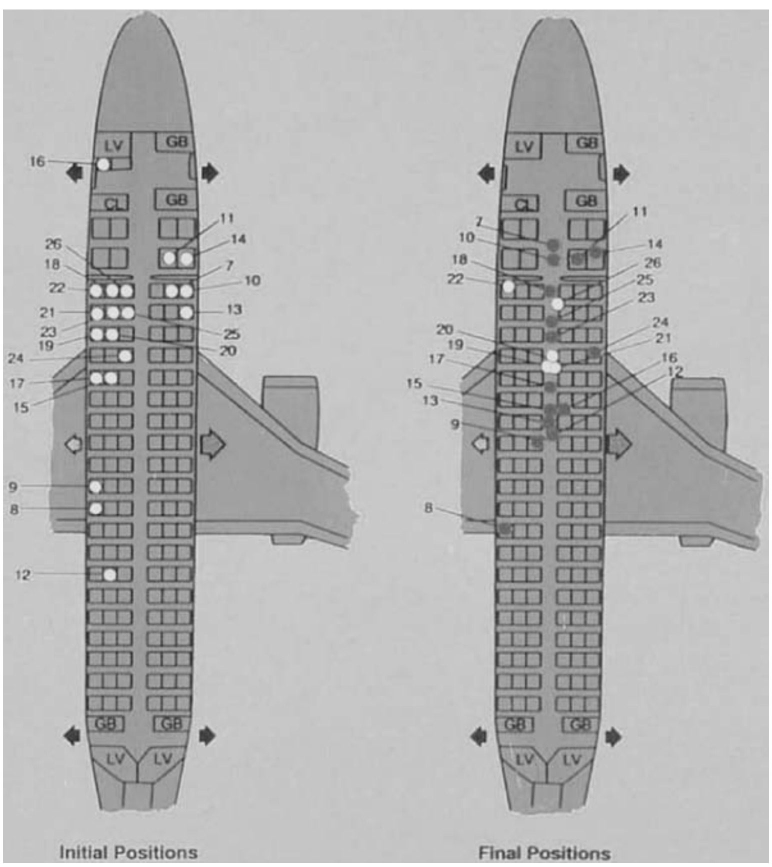


FIGURE 25-56 Diagram of assigned seating of fatalities in B737 and body recovery location with COHg and CN coding.

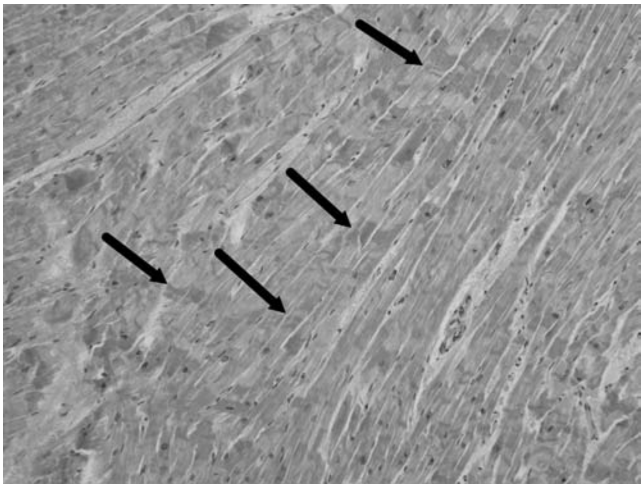


FIGURE 25-57 Artifactual myocardial contraction banding in a aviation fatality due to trauma with no postcrash fire and no antecedent medical cause of incapacitation (photo courtesy of J. Duflou).

in aviation accidents, possibly as a result of sudden stretching of the cardiac myocytes, that may cause a microscopic lesion which is indistinguishable from contraction band necrosis. They also highlight that although contraction-banding necrosis is reliable and one of the earliest histological changes in myocytes, resulting from myocardial ischemia, there are other determinants of such injury which include medical conditions such as intracranial hemorrhage, head injury, asthma, drowning, repeated defibrillations, cardiac surgery, electrocution, catecholamine release, and the use of stimulants such as cocaine and amphetamines. Therefore, the authors caution that contraction band necrosis-like lesions in isolation should not be considered as evidence of acute myocardial ischemia in cases of massive trauma. Figure 25-57 illustrates typical contraction-banding necrosis in an aviation fatality with no postcrash fire or preceding medical incapacitation.

Many factors influence the reliability of various laboratory tests. Investigators should carefully consider the reliability of the test methods used by a particular laboratory, the technical ability of the technicians, and the quality control procedures in use when they select a laboratory to perform toxicology analysis. They must also collect the specimens carefully to avoid contaminating the containers. The indelible ink markers used to label containers may be a source of contamination with organic solvents.

Soil, vegetation, and fuel may contaminate the specimens at the crash site, and immersion may dilute the concentrations of the substances being measured. Fire, burning, and putrefaction may change the composition of the tissues or may produce substances that interfere with the test. The duration and temperature of postcrash exposure have significant effects on the rate of the decomposition process.

The postmortem production of alcohol by bacteria frequently causes difficulty in determining whether the ingestion of alcohol may have impaired a crewmember's judgment. The bacterial production of alcohol usually amounts to less than 50 mg/100 g of tissue, but in rare instances, the production of more than 200 mg/100 g has been observed at the CAMI.

Aircraft accidents are not new but they are rare, with the result that only a relatively small number of persons obtain much experience in aircraft accident investigation. As a result, when called on to participate in an accident investigation, investigators make many mistakes of omission and commission. They can avoid the most serious mistakes utilizing multidisciplinary teams, by careful planning, and by following logical steps, such as the six steps recommended by the JCAP. Determining the role of the participants and the jurisdiction to conduct the investigation is important, and seeking continuing medical education in medical accident investigation and its related forensic disciplines is necessary to stay current.

Identifying the victims is an unpleasant and difficult matter in highly fragmented human remains, which necessitates new tools to handle the DNA information such as Short Tandem Repeats. Frequently, the families of the deceased press for immediate release of identifications and bodies. Planning and organization are essential. Someone must obtain sufficient antemortem records before identification can be possible. Once these data are obtained, examination of the bodies and application of various identification techniques, such as fingerprint, dental, radiologic, and DNA methods, can proceed rapidly.

The acceleration forces, cockpit configuration, nature of the accident, occupant kinematics, and restraint system design determine injury patterns. Investigators can conveniently classify injury patterns by cause: traumatic, environmental, or preexisting disease factors.

The investigation can be difficult, but the procedures are not too onerous, and new tools are enhancing what investigators can do in medical accident investigation. However, investigators must collect and assimilate much information in a short period for use in the immediate investigation and to facilitate long-term research. They must not draw conclusions too quickly lest they make irreparable mistakes and possibly miss an opportunity to improve safety. They can take comfort in knowing that their activities will benefit aerospace safety and that they will likely see results of their contributions in a relatively short period.

ACKNOWLEDGMENTS

Thanks to William M. Morlang, Robert R. McMeekin, Harry L Gibbons, Richard G. Snyder, Roy L. Dehart, and Kenneth N. Beers, Charles Ruehle and Charles Springate—colleagues, mentors, contributors and authors of prior chapters in the first and second editions of *Fundamentals of Aerospace Medicine*, from whom we have drawn much material and education.

REFERENCES

1. NTSB. *Notification and reporting of aircraft accidents or incidents and overdue aircraft, and preservation of aircraft wreckage, mail cargo, and records definitions, 49 CFR, part 830.2*. Washington, DC: U.S. Government Printing Office, 1994.
2. Microsoft. *Encarta world english dictionary*. Seattle: Microsoft Corporation, 1999.
3. NAIMS. Aviation safety statistical handbook NAIMS ATX-400: Department Of Transportation FAA National Airspace System Information Monitoring System, 2007.
4. NTSB. *Safety report: survivability of accidents involving part 121 U.S. air carrier operations, 1983 through 2000*. Report No.: NTSB/SR-01/01: National Transportation Safety Board, 2001.
5. Villarreal C. *Uses and misuses of risk metrics in air transportation: National Research Council*. NRC, 1988.
6. DOT/FAA. *Omnibus transportation employee testing act of 1991 in public law 102–143*, 1991.
7. NTSB. *Aircraft accident report: DCA88MA017 Trans-Colorado Airlines, flight 2286, Fairchild Metro III, SA227 AC, N69TC, January 19, 1988*. Washington, DC: U.S. Government Printing Office, 1989.
8. NTSB. *Aircraft accident report: FTW96FA027, Talon Air Service, Beech 65-B80, N9NP, October 26, 1995*. Washington, DC: U.S. Government Printing Office, 1996.
9. NTSB. *Investigation guides and procedures 2007*. Available from: http://www.ntsb.gov/info/inv_guides.htm.[cited July, 2007].
10. NTSB. *Safety report: general aviation crashworthiness project, phase one*. Report No. NTIS PB83-917004. Washington, DC: U.S. Government Printing Office, 1980; June 27, 1983.
11. NTSB. *Safety report: general aviation crashworthiness project, phase two, impact severity and potential injury prevention in G.A. accidents*. Report No. NTIS PB85-917002. Washington, DC: U.S. Government Printing Office, March 15, 1985.
12. NTSB. *Safety report: general aviation crashworthiness project, phase iii, acceleration loads and velocity changes of survivable general aviation accidents*. Report No. NTIS PB85-917016. Washington, DC: U.S. Government Printing Office, September 4, 1985.
13. DeHaven H. Beginnings of crash injury research. *Proceedings of Thirteen Stapp Car Crash Conference*. Boston: Society of Automotive Engineers, Inc., December 2–4, 1969; Two Pennsylvania Plaza, New York, NY 10001.
14. Haddon W. Advances in the epidemiology of injuries as a basis for public policy. *Public Health Rep* 1980; 95(5):411–421.
15. McMeekin R.Patterns of injury in fatal aircraft accidents. *Aerospace pathology*. Chicago: College of American Pathologists Foundation, 1973:86–95.
16. Hill I. Mechanism of injury in aircraft accidents—a theoretical approach. *Aviat Space Environ Med* 1989; 60(7 Pt 2):A18–A25.
17. Bangdiwala SI. Methodological considerations in the analysis of injury data: a challenge for the injury research community. In: Tiwari D, Mohan G, eds. *Injury prevention and control*. London and New York: Taylor & Francis, 2000:35–48.
18. Ricaurte E, Gallimore JJ. *Development of specifications for an interactive aircraft accident data collection and analysis system*. Oklahoma City: FAA Civil Aerospace Medical Institute, U.S. Department of Transportation, Federal Aviation Administration, 2006:100.
19. Reason J. Human error: models and management. *Br Med J* 2000;320(7237):768–770.
20. *Safety in air hearings (3 parts), before a subcommittee, pursuant to Senate Resolution 146*. *Senate Committee on Commerce*: United States Congress 1936–1937.
21. Armstrong JA, Fryer DI, Stewart WK, et al. Interpretation of injuries in the Comet aircraft disasters. *Lancet* 1955;1:1135–1136.
22. International Civil Aviation Organization (ICAO). *Chicago convention on International Civil Aviation*. 1944.
23. NTSB. Accident/incident investigation procedures Title 49 U.S.C. Chapter VIII: Part 831.
24. JCAP. *Memorandum no. 1: an autopsy guide for aircraft accident fatalities*. Washington, DC: Joint Committee on Aviation Pathology, 1957.
25. Wiegmann D, Shappell S. *A human error analysis of commercial aviation accidents using the human factors analysis and classification system (HFACS) OAM report*. Report No. AM-01/3. Washington, DC: U.S. Government Printing Office, 2001..
26. Fryer D. The medical investigation of accidents. In: Gillies JA, ed. *Textbook of aviation physiology*. Oxford: Pergamon Press, 1965:1200.
27. Leclair B, Shaler R, Carmody GR, et al. Bioinformatics and human identification in mass fatality incidents: the world trade center disaster. *J Forensic Sci* 2007;52(4):806–819.
28. Slottje P, Huizink AC, Twisk JW, et al. Epidemiological study air disaster in Amsterdam (ESADA): study design. *BMC Public Health* 2005;5(1):54.
29. Hays M, Stefank JX, Cheu DH. Planning an airport disaster drill. *Aviat Space Environ Med* 1976;47.
30. Lane JC, Brown, TC. Probability of casualties in an airport disaster. *Aviat Space Environ Med* 1975;46:958.
31. Charles MT, Settle AK. United flight 232: Sioux city's response to an air disaster. *Organ Environ* 1991;5(1):77–90.
32. Morlang W. Mass disaster management. In: Stimson P, Mertz, CA, eds. *Forensic dentistry*. Boca Raton: CRC Press, 1997:185–236.
33. Clark M, Clark SR, Perkens DG. Mass fatality aircraft disaster processing. *Aviat Space Environ Med* 1989;60(Suppl 7):A64:73.
34. Morlang W. Mass disaster management syllabus and plan. Washington, DC: *Oral and Maxillofacial Pathology Department* Armed Forces Institute of Pathology.
35. Brannon R, Morlang WM. Tenerife revisited: the critical role of dentistry. *J Forensic Sci* 2001;46:722–725.
36. Brannon R, Morlang WM. Jonestown tragedy revisited: role of dentistry. *J Forensic Sci* 2002;47:3–7.
37. Brannon R, Morlang WM. The crash of LOT flight 007: dental identification. *J Forensic Sci* 2002;47:1323–1325.
38. Brannon RB, Morlang WM, Smith BC. The Gander disaster: dental identification in a military tragedy. *J Forensic Sci* 2003;48:1–5.
39. Brannon R, Morlang WM. The USS Iowa disaster: success of the forensic dental team. *J Forensic Sci* 2004;49:1067–1068.
40. Lichtenstein JD. Role of radiology in aviation accident investigation. *Aviat Space Environ Med* 1980;51:1004–1014.
41. Hill IR. Dental identification in fatal aircraft accidents. *Aviat Space Environ Med* 1980;51:1004–1014.
42. Morlang W. Forensic dentistry. *Aviat Space Environ Med* 1982;53:27–34.
43. OTA. *Genetic witness-forensic uses of DNA tests*. U.S. Office of Technology Assessment, 1990.
44. Petty A, McMeekin RR. Laboratory examination of unidentified tissue fragments found at aircraft sites. *Aviat Space Environ Med* 1977;48.
45. Mason JK. Passenger tie-down failure: injuries and accident reconstruction. *Aviat Space Environ Med* 1970;41.
46. Eiband A. *Human tolerance to rapidly applied accelerations*. Washington, DC: National Aeronautics and Space Administration, June 1959.
47. Coltart WD. Aviators astragalus. *J Bone Joint Surg Br* 1952;34:546–566.
48. Dummit ES, Reid RL. Unique tibial shaft fractures resulting from helicopter crashes. *Clin Orthop* 1969;66:155–158.
49. Smelsey SO. Diagnostic patterns of injury and death in USAF aviation accidents. *Aerosp Med* 1970;41:563–566.
50. Pettyjohn F, McMeekin RR. Coronary artery disease and preventive cardiology in aviation medicine. *Aviat Space Environ Med* 1975;46:1299–1304.
51. Raboutet J, Raboutet, P. Sudden incapacitation encountered in flight by professional pilots in French civil aviation, 1948–1972. *Aviat Space Environ Med* 1975;46:80–81.

52. Duflou J, Nickols G, Waite P, et al. Artefactual contraction band necrosis of the myocardium in fatal air crashes. *Aviat Space Environ Med* 2006;77:944–949.
53. Washington E, McDonald K, Shojania KG, et al. *The autopsy as an outcome and performance measure*. Evidence Report/Technology Assessment No. 58. Rockville, 2002.
54. Benson OO. Coronary artery disease: report of fatal cardiac attacking a pilot while flying. *J Aviat Med* 1937;8:81–84.
55. Ricaurte EM, DeJohn CA, Satterlee R, et al. Incidental cardiovascular findings in U.S. civil aviation pilots involved in fatal accidents. *78th Annual Scientific Meeting of the Aerospace Medical Association, AsMA*. New Orleans: AsMA, 2007.
56. Balfour A. Sarcoidosis in aircrew. *Aviat Space Environ Med* 1982;53: 269–272.
57. Pettyjohn FS, Spoor DH, Buckendorf WA. Sarcoid and the heart, an aeromedical risk. *Aviat Space Environ Med* 1977;48: 955–958.
58. Mason J. Previous disease in aircrew killed in flying accidents. *Aviat Space Environ Med* 1975;46.
59. Pounder D. Dead sober or dead drunk? *Br Med J* 1998;316(7125):87.
60. Canfield DV, Kupiec T, Huffine E. Postmortem alcohol production in fatal aircraft accidents. *J Forensic Sci* 1993;38(4):914–917.
61. Zeller A. Alcohol and other drugs in aircraft accidents. *Aviat Space Environ Med* 1974;46:1271–1274.
62. Smith PW, Lacefield DJ, Crane CR. Toxicological findings in aircraft accident investigation. *Aviat Space Environ Med* 1970;41.
63. Canfield DV, Hordinsky J, Millett DP, et al. *Prevalence of drugs and alcohol in fatal civil aviation accidents between 1994 and 1998*. Washington, DC: U.S. Government Printing Office, 2000.
64. Canfield D, Chaturvedi A, Boren H, et al. *Abnormal glucose levels found in transportation*. Washington, DC: Civil Aerospace Medical Institute, 2000.
65. Dominguez AM, Halstead JR, Chinn HI, et al. Significance of elevated lactic acid in the postmortem brain. *Aerosp Med* 1960; 31.

RECOMMENDED READINGS

Aerospace Medical Association. *A primer on aircraft accident investigation for the aerospace medicine practitioner*. Alexandria: Aerospace Medical Association, 2000; http://www.asma.org.

Rainford DJ and Gradwell DP, eds. *Ernsting's Aviation Medicine*, 4th ed. Oxford: Hodder Arnold, 2006.

Previc F, Ercoline B, *Spatial Disorientation in Aviation*, AIAA, 2004.

Reason J *Human error*. Cambridge: Cambridge University Press, 1990.

CHAPTER 26

Aviation Medicine in Unique Environments

Thomas F. Clarke, Roy L. DeHart, Nils Erikson, James A. King, Cheryl Lowry, Kenneth A. Williams, and Robert Johnson

> Never tell people how to do things. Tell them what to do and they will surprise you with their ingenuity.
>
> —*George S. Patton*

No other medical specialty provides its practitioners the opportunities to practice their craft in such a broad array of environments as the aerospace medical professional (AMP). The nature of aviation medicine often leads those who practice it into austere or otherwise challenging environments and situations that in turn have profound effects on their patient and their practice. It is a basic tenet of medicine that the environment plays a significant role in defining the stressors that affect the patient population in the form of the disease and injury threats they face. The environment also affects the responses, both physiologic and behavioral, which individuals may generate to counter those threats. Furthermore, the same environment may profoundly alter the way the aerospace medicine professional practices the art and science. It can place significant limits on the equipment, supplies, and access to expert consultation among other parameters. To succeed, the aerospace medicine professional must anticipate these limitations and prepare to mitigate them. Furthermore, the AMP must find appropriate compromises, which allow him/her to be able to provide the care needed within the overall parameters of the mission at hand.

The opportunities for individual AMPs to work outside of their usual practice environments will continue to increase. We live in a time of frequent population crisis. A rapidly expanding global population increases the likelihood of conflict between groups as they find themselves increasingly in competition for limited resources and opportunities. Additionally, a higher population density increases the odds that any given catastrophic event will affect even larger populations. Furthermore, modern communication technologies mean that events from halfway around the world will quickly become news at home. When political leaders look to who can provide medical care in time of a contingency they will continue, as they have done in the past, to look to AMPs. They will be called upon to care for the aviators and support personnel who provide the airlift necessary to bring resources to bear on acute disasters. In addition, history has shown that AMPs have the training, the experience, and the assets to respond successfully to such crises.

In this chapter, we will discuss general principles of medical practice as they pertain to the preparation and execution of medical support missions to the unique environments one may be called to practice in. We will discuss principles of patient movement during contingencies and further discuss several specific unique environments both to illustrate their particular features and to serve as examples of how basic principles may be applied to diverse environmental challenges.

OPERATIONAL/CONTINGENCY MEDICINE IN THE AUSTERE ENVIRONMENT

In this section, we focus on the principles of operational/contingency medical response to austere medical environments. We will discuss general medical deployment preparation and outline the steps needed to first produce an accurate medical threat assessment as well as develop a threat mitigation plan. We will touch on basic principles of equipment and supplies for the operational/contingency environment. Finally, we will discuss principles of training and personnel preparation for this capability.

General Principles of Deployment Preparation

When considering operational/contingency medical responses in austere environments two broad potential scenarios set the focus for operational planning. In one category, our organization is going to perform some mission or task in an area where medical capability is underdeveloped. The AMP's medical capability is needed to fill the medical void, specifically in terms of caring for the aviators and other support personnel that are part of that mission. We plan to "care for our own" with maybe some assistance provided to local peoples in cases that are either emergencies or politically necessary. In another category, our medical unit is reporting to an area where the medical capability is either underdeveloped and/or it has been seriously compromised by some natural or man-made disaster. In this case, our primary mission may be to provide care to the local population as well as support other aid workers who are there to support the situation in nonmedical roles.

The tremendous variety of environments the AMP may be required to respond and operate in will frustrate any attempt to have a single operational plan that will cover all scenarios. What is needed is a process that can be used to assess the situation to be supported, define the medical threats, and develop a plan to mitigate those threats while insuring successful mission completion. It is important to remember that the delivery of medical care, *per se*, is rarely the primary mission goal and more typically serves a greater good. The ability to maintain focus on the broader goals will help the AMP to tailor the medical support piece such that it contributes to overall mission accomplishment and increases the likelihood of success.

The Process

The basic process of performing a medical assessment of the situation requires that four general steps be completed: gathering intelligence, identifying threats, developing threat mitigation strategies, and development of emergency plans.

A. ***Gathering intelligence*** Obviously to plan, we must have an understanding of the situation. This understanding must include the chronic and acute medical situations in the area as well as the expected mission that you and the personnel you are supporting, will be executing. The availability and accuracy of "facts" concerning the situation are often limited at this point. Therefore, there are advantages to thinking of what you "know" about the situation as less than certain. The AMP must recognize that even the best intelligence available will still involve some uncertainty. Wisdom dictates maintaining a conservative posture and not relying excessively on any particular piece of information. It also implies a need to continually update the understanding of the situation as new data become available. Both of these considerations will benefit the AMP as she/he develops and refines plans for medical support of the mission.

There are six basic intelligence or information categories that ideally should be understood to begin the planning process. These include: overall mission goals, physical threats/security, populations involved, geographic locations, anticipated environmental interactions, and billeting and messing.

1. ***Overall mission goals*** As stated previously, it is rare that the delivery of medical care will be the overriding goal in a disaster situation. Almost all disasters have at their root problems greater than limited medical care. It is frequently tempting for the medical personnel to focus exclusively on the delivery of medical care. However, this failure to understand the greater mission requirements and to see medical capability as simply one of the tools to achieve those overall goals, may significantly limit chances of their success. In the worst situations, the medics may actually divert limited resources away from areas where they may do the most good in a myopic effort to address the medical issues they are focused on.

   In cases of natural disaster, the reestablishment of infrastructure and rebuilding of communities is the overarching goal. Medical capability is an important requirement to support rescue workers and community development teams who are more directly involved in those tasks. Care to the local population may also be a requirement, especially early on. However, provision of care to the disaster victims must be administered cautiously to avoid negatively affecting the local capability and leaving the population less well served in the long run. The primary goal of medical care provided to the local population should always be the strengthening of the indigenous medical capability with individual benefit secondary.

   In cases of man-made disasters from war or terrorist activity or even in chronic situations of ineffective local administrations and a degraded social structure, the primary mission goal will be establishment of a peaceful and more self-sufficient society. Medical care in these cases may simply be one way of winning the "hearts and minds" of a population to assist in pushing a more acceptable political agenda. Political necessity may divert medical care away from the areas where it appears it would be better utilized. This can be an ethical dilemma or a difficult situation for some medical professionals. However, failure to recognize this reality may lead to unproductive use of medical resources and even undermining of the overarching goal.

   In any case, it is important that the medical personnel going to a crisis environment understand the broader nature of the problem as well as the overarching goals of the nonmedical groups who respond. Dramatic "saves" by the visiting medics can serve as beacons of hope to build confidence and support or they can simply undermine the local medical providers and leave the area less well served in the long run. Decisions about how and when to apply medical capability to these complex situations must be considered within the larger context.

2. ***Physical threats/security*** A basic understanding of physical threats against your medical organization and/or the personnel or population you are going to support is vital to your planning. It assists in estimating the types, quantity, and severity of injuries you may expect to see. In military terms, this would be summarized as the enemy situation and would include estimates on the number of enemy, their tactics, and what weapons they are likely to use. This information is germane to civilian missions as well. The security situation, threats of terrorist action, and other violent crime that might threaten the medical and other personnel is vital to planning personnel, equipment, and evacuation requirements of the mission. In most cases, the AMP will play an important role in advising the leadership of the overall response about security limitations and the potential impact intentional trauma will have on both safety and the medical situation. In almost all response situations, input from security professionals is vital to gathering accurate intelligence as well as the development of security measures to insure unit safety.
3. ***Populations involved*** In the case of missions where medical assistance is simply a support piece of a larger mission, there is a need to know the demographics of the personnel supported as well as the general population health status. A group of older contractors tasked to support construction of a dam will present very different medical demands than would a similarly sized group of active duty Navy Seabees doing the same job. Furthermore, if supporting an international effort, it is valuable to know how many personnel from what other countries will be there assisting. What is their baseline level of medical care and what capability are they going to bring in their support? More importantly, their existing expectations and cultural practices help to appropriately guide the medical care delivery.

   Additionally, it is vital that you have a reasonable estimate of the demographics of the local population. The AMP should understand the total population size, and how the population is distributed by age, gender, and existing disease burden. In assessing the location, it is important to have an overall sense of what the health status is, (or in some cases, what it was before the event that is bringing you there). Similarly, a baseline assessment of medical infrastructure and capability is useful. Often the actual "on the ground" case is not as clear-cut as originally conceived. Even in some very underdeveloped areas, modern and high-quality medical care may be available but not in the same cross sections. For example, physician capability may be very good while nursing and paraprofessional care is much more limited and will require the AMP to plan to "fill these gaps."

   A basic understanding of culture and customs is valuable and prevents mistakes which, at the least, may be embarrassing but which can represent a real barrier to the provision of care delivery. Though often overlooked, it is important to understand some of the health care systems and management in the location you will be operating. Specifically, try to assess how medical care will be compensated for and what reasonable and customary compensation is. It may be prudent to charge for the care you and your organization provide if only to avoid undercutting local medical infrastructure. In the most optimal situations, the responding medical personnel will make great efforts to work within the existing care system. This may require greater cultural sensitivity and sacrifices of autonomy but ultimately can lead to the best overall outcomes. Successful efforts to strengthen the local capability will pay dividends long after your individual efforts are forgotten. Even in situations where your primary role is support of a response team and direct care of locals is not anticipated, this knowledge will be valuable.
4. ***Geographic locations*** The next area that you must to understand is the location(s) to be deployed. This may represent what most of us think of as "the environment." Information is needed about temperatures, humidity, precipitation, altitude, and prevailing winds in addition to understanding the insect vectors and other animal threats that might affect personnel. We need to have a sense for the nature of the geography—is it flat and easy to move across or rugged to the point that land travel is difficult? Are the roads passable and how quickly? It is also important to recognize that, in many contingency situations, success at one location may result in movement to one or more subsequent locations. The AMP should plan for not only the first site but also for potential follow-on locations.
5. ***Anticipated environmental interaction*** In addition to the medical capabilities and shortfalls of a location, one must understand the environment in terms of the expected interface it may have with those deploying to the site with you. A contaminated sewer system presents a very different threat to a teacher tasked to teach agriculture skills in a classroom than it does to a communications worker who must enter confined spaces partially filled with runoff to get to the telephone lines. Personnel working at night may be exposed to different set of disease and injury threats than those working in the day. Again, a basic understanding of the overarching mission as well as the roles that various responders outside of the medical support piece will play is vital to planning and preventing diseases and injuries that are likely to present.
6. ***Billeting and messing*** Where support personnel live and eat is central to planning and will make a huge difference in the quantity and types of diseases you are likely to encounter during your mission. The facilities in which personnel sleep and rest will similarly alter

the effects of ambient temperature and humidity as well as profoundly affect the threat of vector borne disease. The source of food and how it is procured and prepared will similarly have tremendous impact on the threat of food and waterborne disease, which is often the greatest medical threat to the visiting personnel. This is another area in which the aerospace medicine professional must recognize his/her role as advisor to the leadership concerning what types of facilities are necessary and how questionable facilities can be improved to reduce the risk of disease.

B. ***Identifying threats and developing mitigation strategies*** Once the AMP has gathered and assessed the best possible intelligence about the mission, she/he can move on to the identification of specific disease and injury threats. The nature and magnitude of these threats are highly dependent on the intelligence that will need to be gathered. In fact, the medical threat assessment is really just a more specific list of threats based on that intelligence. Therefore, additions or changes to the intelligence will likely affect the threat assessment as well.

As stated previously, each situation is different and there is no single threat assessment, which can be developed that can meet the varied demands. Rather, what is required is an iterative process that assists the AMP in considering all the potential threats and deciding which are pertinent to the situation at hand. The specific format is not important as long as it includes all of the potential threats that an environment may pose. What follows is simply one format that has been developed to address the various threat categories.

1. ***Intentional injury*** This category includes various violent attacks that may occur against responders or locals you may be tasked to care for. In war scenarios, this may include overt attack by enemy forces. Less openly hostile situations still often include the threats of terrorist actions or simply violent crime. In all cases, the AMP may be faced with a variety of severe injuries including penetrating and blunt trauma, serious burns, and blast injuries. These injuries put a significant strain on the limited medical resources that have been brought to the situation. Furthermore, depending on the mission and the tolerance for such events, they may significantly compromise the willingness of sponsoring nations or nongovernmental groups to continue in support of the mission.

   Prevention of such injuries is the most important effort the AMP can take in addressing this threat. However, preventive strategies must still support accomplishment of the mission. For example, the most effective preventive measure may be to not engage in the mission at hand—hardly appropriate in most situations. Indeed the acceptable level of risk is more a political and strategic decision than a medical one. However, it will fall to the AMP to act in his/her consultant role to discuss with leadership the effects that the potential trauma will have as well as the need to have adequate security and force protection measures in place. Individual actions should be considered and try to provide input as to how the threat of intentional injury measures against the potential value of the action. Insuring that personnel have appropriate protective equipment for the situation such as Kevlar helmets, bulletproof vests, and ballistic eye protection can can markedly improve survival in cases of intentional trauma. Additionally, efforts to insure that nonmedical personnel are well trained in trauma first aid may allow for injured personnel to get the immediate care they need to survive until they can enter the medical system. Depending on the nature of the threat, this first aid may require airway and intravenous (IV) capability.

2. ***Unintentional injury*** Motor vehicle accidents (MVAs) continue to be a common cause of death and disability in working age individuals as well as the number one cause of death in tourists. Austere environments often present a very different and in many ways more hazardous driving environment than that which the responder may be used to. The threat of MVAs to personnel should not be underestimated.

   Work-related injuries can also be a significant threat to responders. Especially in more dramatic scenarios, those wanting to help may be motivated to cut corners to accomplish tasks quickly in an effort to help. These motivations can backfire and result in excess injuries to responders and a loss of care capability. As response situations become more chronic, sports injuries and other recreational injuries can become significant sources of trauma.

   Efforts to reduce unintentional injuries will consist primarily of policy decisions, which must be made and enforced by the mission leadership. The role of the AMP is to advise the leadership as to what limitations may be the most appropriate. There are several policies that are likely to assist in the prevention of unintentional injuries. The most important are informed travel guidance and limitations. The first step is to insure that personnel never travel alone. After that, insuring that personnel limit travel to appropriate vehicles will reduce the chances of MVAs and other threats. Travel by motorcycles and "hooptees" increases risk unacceptably and is rarely necessary. Travel in taxis must be done with care to insure that the vehicle is a taxi registered to a legitimate company. Careless use of taxis can result in robbery or other dangerous crime situations. In some areas, the only safe way to travel is in secure vehicles contracted from security agencies. Again, these limitations are ones that will be decided and enforced by the nonmedical leadership.

3. ***Disease threats*** In most situations, diseases are the greatest threat to both the responder and local populations. For the purposes of developing the threat assessment, they can be grouped into several categories.
   a. ***Food and waterborne diseases*** Bacterial, viral, and parasitic diarrheal diseases represent a major

threat to responders. This threat can be greatly exacerbated in times of humanitarian crisis where food and water sources are frequently compromised. More significant conditions such as hepatitis A and E as well as typhoid fever are also tremendous threats in this environment. Rare will be the situation in which food and waterborne diseases are not a major threat to the responding population and the success of the mission.

On the surface, avoidance of food and waterborne disease would seem simple. In the "*en vivo*–real world" environment it can be much more difficult. People like food and will aggressively seek "opportunities" to infect themselves with these community-acquired diseases. Trying to limit the food that personnel eat to approved and acceptable sources seems to be the first logical step. However, history has shown that unless your situation is such that there are no sources of food outside those you can control, personnel will get around any limitations you attempt to impose. A less paternalistic approach that is often more successful is to educate them on what can be safely consumed and what cannot. Baked, boiled, bottled and peeled (BBBP) is an easy to remember tool that reminds personnel of the foods that are less likely to result in disease. Items taken hot off the grill or hot out of the oven are relatively safe as are foods that are naturally peeled to eat. Baked breads remain relatively safe while fresh. Commercially bottled drinks are generally safe though water, which can be easily bottled by locals using unsafe sources, is suspect. Soda and beer are the safest as the basic bottling procedures exclude survival of bacterial or viral diseases. Ironically, the greatest threat from food and drink comes from sources that may be considered "healthy" at home. Salads and other leafy vegetables as well as fresh juices may be healthy choices at home but are extremely high risk in much of the developing world. It is sometimes ironic that medical personnel who may be focused on "healthy lifestyles" have a difficult time initially accepting this situation. The good thing is that it is relatively easy to educate personnel about how to eat in the developing world and avoid disease while still allowing them to enjoy what the local economy has to offer.

Recognizing that almost no food or water strategy can completely prevent risk, prevention and treatment measures need to be insured. Hepatitis A and typhoid vaccines are near constant requirements.

Antibiotics, while not necessarily a common part of diarrhea treatment in the developed world, have a more frequent role in the developing world. Additionally, depending on your situation, the ability to have IV therapy available for patients who become significantly dehydrated may be very limited. Intravenous solutions are relatively heavy and can be prohibitive in amounts needed to treat diarrheal outbreaks. Oral rehydration solution is a much more rational approach in a weight-limited environment. Not only can the ingredients be found in almost any location you might be operating in, if necessary, it can be included in the supply kit at little cost.

b. ***Vector-borne diseases*** Conditions such as malaria, dengue, yellow fever, leismania, bartonella, trypanosomiasis, plague, as well as a host of encephalitic and hemorrhagic fevers can all represent significant threat to populations in many world environments. The global distribution of these conditions and the threat they present are typically well understood and available through various intelligence sources. It is worth noting that humanitarian disasters may break down previously successful control measures and result in the condition emerging anew or reemerging where it was previously controlled. These are conditions that can rapidly compromise a response team and quickly take them from an asset to a liability in a disaster scenario.

Most of the preventive measures that can be deployed against vector-borne threats will be the same irrespective of the geographic location or the specific threats. The most important preventive measures are barriers that prevent the insect from biting and passing the disease to the individual. In locations where the billeting situation does not provide adequate mosquito prevention, pyrmethrin-treated bed nets are the single most effective intervention you can provide. The more modern versions are compact, packable, and extremely easy to use.

In addition to bed nets, leadership-directed wear of appropriate, pyrmethrin-treated clothing by personnel could greatly reduce the risk of mosquito and other biting insect vector disease. This is especially important during the dawn/dusk time period when personnel may be off duty and relaxing in typically less insect protective clothing. The final prevention barrier is the application of diethyl-m-toluamide (DEET) insect repellent to the skin at appropriate intervals. The best DEET preparations are those which are lower concentrations (~20%–50%) but which are microencapsulated to provide a longer lasting and more consistent level at the skin.

Beyond barrier prevention, specific disease interventions should be undertaken where appropriate. Immunizations against specific diseases such as yellow fever and Japanese encephalitis are important in the regions they are found. Additionally, prophylaxis against malaria is an effective and critically important preventive strategy in the large areas of the world that are affected by this condition.

Although there are a variety of medications available, determination of which one is best for the individuals who are going to deploy can be a daunting task. Weekly dosing of Chloroquine, Mefloquine or Malarone, or daily application of Doxycycline or Primaquine are among the more commonly used prophylactic malaria medications. The website at the Centers for Disease Control and Prevention (CDC) provides up-to-date risk and resistance guidance for common prophylactic measures and medications. Each has its advantages and disadvantages, some of which can be significant side effects in certain patients. Chloroquine is well tolerated by most patients but resistant organisms have greatly limited its geographic usefulness. Mefloquine is also reasonably well tolerated although neurologic side effects and political fallout from personnel who have blamed criminal behavior on the drug may be significant concerns. Malarone, which is a combination of atovaquone and proguanil hydrochloride, is approved only for the prevention and treatment of falciparum malaria but appears to work well for all malaria species. It is well tolerated and effective but relatively expensive. Doxycycline is commonly used but has several negatives including a daily use requirement, gastrointestinal (GI) upset, and sun sensitivity. Finally, the use of primaquine daily throughout the exposure period may be effective but cannot be used in G6PD deficient patients and represents off-label use.

In addition to prophylactic medications, the AMP must insure the medications for treatment of suspected and confirmed acute malaria infection is available. This is especially important for falciparum malaria that has the potential to be rapidly fatal. Malaria infection is classified as severe if infection is associated with impaired consciousness, coma, seizures, shock, renal failure, hemoglobinuria, pulmonary edema, acute respiratory distress syndrome (ARDS), diffuse intravascular coagulation, acidosis, severe normocytic anemia, or a parasitemia of more than 5% of erythrocytes. These severe cases typically require inpatient treatment in an intensive care setting with a combination of IV and oral medications including Quinidine gluconate. Quinidine can be somewhat difficult to find and must be arranged for before the need arises. Cases without those complications listed are referred to as *uncomplicated* and can be treated with a variety of oral medications in an outpatient setting.

Over time, specific medications and recommendations may change. The types of malaria present in specific locations and the resistance of those organisms to various medications may drift. The AMP will need to insure that she/he is up to date with current recommendations for the region being supported to provide prevention and treatment for those personnel under his/her responsibility. Organizations like the CDC in the United States can be relied on for up-to-date recommendations either on their website or in hardcopy form. (http://www.cdc.gov/malaria/diagnosis_treatment/tx_clinicians.htm) Those supporting military operations may have the luxury of mandating malaria prophylaxis for "the force." It is important for the military AMP to remember that enforced prophylaxis must be done in keeping with the U.S. Food and Drug Administration (FDA)-approved indications of the medications. Civilian organizations may have more latitude to use medications "off-label" but they are required to apply these medications one-on-one with individual risk benefit calculations done for each patient. In the end, the AMP must have a detailed understanding of malaria medications before planning operations in a malarious area or risk mission-compromising infections that malaria can and has presented to operations throughout our history.

c. ***Person to person*** Conditions that are spread person to person have the capacity affect deploying personnel as well as to present as large outbreaks in humanitarian disasters where the population immune response may be compromised and where large groups of people are brought in close contact. Threats include pneumonias, many of the vaccine preventable diseases such as measles, as well as the sexually transmitted diseases and mycobacterial infections of tuberculosis (TB) or leprosy. The medical condition of the native population as well as the customs and interactions they will have with the response personnel will assist in estimating how great the threat will be.

Vaccine-preventable diseases are thankfully straightforward to address using the specific vaccines. Sexually transmitted disease threats are highly dependent on the behavior of the deploying personnel and can largely be prevented by appropriate education before and during deployment. The enormous risk of human immunodeficiency virus (HIV) and acquired immunodeficiency syndrome (AIDS) has made educating personnel and gaining their cooperation easier although efforts to curtail sexual activity completely will rarely succeed. It is still vital that the AMP be available to provide safe sex alternatives and education as even the most well-intentioned traveler can be overwhelmed by the availability of unsafe sex opportunities in much of the developing world.

Additionally many operations place personnel at risk for occupational exposure to blood and body fluids. The ability to test sources may be limited and in some cases source testing may not be an option. The AMP does not need to be an expert in HIV treatment but she/he should understand the basics of post–exposure prophylaxis including expected side effects. Additionally, the AMP must insure that post–exposure prophylactic medication on hand in the case of possible exposure until the source can be tested or until contact information can be evaluated and further recommendations provided.

Among the most difficult conditions to protect personnel from are the mycobacterial infections. Leprosy transmission is so slight that in practicality it represents a small threat. TB is a real risk and skin testing to assess for latent TB infection should be done before entering and between 3 and 6 months after leaving a high-risk area. Complete recommendations on testing and treatment of latent and active TB are outside the scope of this chapter but can be accessed from one of several frequently updated sources. (http://www.cdc.gov/nchstp/tb/pubs/mmwrhtml/Maj_guide /List_date .htm)

d. ***Animal or water exposure*** Animals and swimming or wading present the risk of unpleasant situations from land-based and waterborne risks. Poisonous reptiles and insects can inflict venomous bites. Larger predator animals in some areas can inflict life-threatening injuries. Thankfully, contact with these is relatively rare. However, exposure to domestic or feral pets is much more common and often even sought after by the responding personnel. These animals can present the risk of bites and scratches and, on a more concerning level, rabies. Swimming or wading carries with it the risk of drowning, hypothermia, and other cold injuries such as immersion foot. Wading or swimming in fresh water bodies in large parts of the world also presents the risk of diseases such as schistosomiasis and leptospirosis.

   Appropriate education of personnel as well as strict application of relatively straightforward leadership-enforced directives such as "no pets or mascots" and "no swimming or wading in natural fresh water bodies" can reduce the risk significantly. If the mission requires care of feral animals, those who may be exposed should be immunized against rabies and provided appropriate equipment and personal protective equipment (PPE) to reduce the risks of bites. If opportunities for recreational swimming are desired, it falls to the AMP to assess the risk and insure that leadership has accurate information about the situation. Only then can they make rational decisions about the risks and benefit of such opportunities to insure that personnel are protected.

e. ***Environmental threats*** Climatic and geographic conditions such as heat, cold, altitude, ultraviolet (UV) exposure, and even pollution present threats to the deploying personnel. Although these conditions seem straightforward, the list of operations that have been completely compromised by heat and cold alone is long and distinguished and spans time from the distant past to near present.

   Severe environmental conditions will reduce a force's capability, even if they successfully mitigate against them. They will, at best, lose time and effort as they deal with environmental challenges. Extreme cold requires clothing that limits dexterity and requires time to don and doff. Extreme altitude will reduce the amount of work even those who acclimate can accomplish while requiring that some personnel be returned due to failure to acclimate. The AMP must recognize these threats and act strongly as the advisor to his commander to inform him as to how the threats will limit his force's capability and require additional personnel to accomplish the same tasks. For example, an organization that requires 400 personnel to perform their typical mission may require an additional 20% to do the same task at a base camp at 12,000 ft elevation.

f. ***Pre-existing disease*** The final issue in consideration of disease threat is the preexisting condition of the individuals to be supported. Injury and disease threats are always experienced in the context of the individual exposed to the condition. The medical condition of personnel is a major factor in determining how they will compensate (or fail to compensate) for many of these threats. This text does not allow for a discussion of the many medical conditions that might affect injury and disease threats in unique austere environments. Nevertheless, the AMP must be aware of the population she/he anticipates supporting and consider the medical condition and fitness that they bring to the situation in trying to do his/her contingency planning. Some conditions may lend themselves to mitigation attempts. Others may simply not be consistent with the planned operation and the AMP may have to take the role of advising his/her commander concerning appropriate physical standards for the personnel selected to support the mission.

4. ***Emergency plans*** Despite the best planning and efforts at prevention, bad things will sometimes happen. Personnel may be seriously injured or may become seriously ill far from access to established medical care. Without access to traditional fixed medical capability or expert consultation, the AMP must insure the basic capability to provide initial stabilization including airway control, advanced cardiac life support (ACLS) capability, bleeding control, as well as blood and fluid

replacement. Depending on the geographic area of responsibility, this initial stabilization capability may need to be available in kits that can be taken easily to the site of injury or to meet the injured as they are brought toward your facility.

For severe trauma, surgical intervention will be required. Discussions and opinions abound about how near surgical capability should be located to areas of potential injury in the deployed environment. All too often, there will not be sufficient surgical assets to position them near all the potentially dangerous operations. The AMP planning the mission must have some appropriate standard for how near surgical capability needs to be. Data to support this kind of decision comes from studies concerning small arms injuries and survival in wars from the U.S. civil war to the recent conflicts in Afghanistan and Iraq. These studies support the added survival value of surgical intervention within 6 hours of point of injury but not necessarily sooner.

To meet the goal of having surgical intervention within 6 hours of point of injury may necessitate bringing organic surgical capability with you as part of your support even when it is not part and parcel of the overall mission. However, in many cases the additional personnel and equipment needed to establish surgical capability in an austere medical environment represents a significant additional logistics burden. In these cases, surgical capability may be found using either host nation or surrounding nation capability. Assessment of these facilities and actual capability may be estimated by written or telephone intelligence before deployment into the area. However, confirmation of the actual capability should have a high priority and be completed as soon as possible after arriving. This includes developing an acceptable understanding with the local hospital and surgeons for access and reimbursement. As this is done, it may be easy to assess other medical capabilities available at the location and further enhance your capability. This will allow the AMP to reduce the chance for unanticipated shortfalls in surgical or other specialty capability that could affect the ability to insure quality care for your aviators and support personnel.

C. ***Communicating with leadership*** Once the AMP has completed the threat assessment and developed mitigation strategies to prevent levels of illness and injury that may compromise the mission, he must communicate these to the people who can implement them. It is rare that the AMP will have authority within the organization that is responding to the contingency to designate or enforce policy. It is, therefore, vital that she/he garner the support of leadership to implement his/her recommendations. AMPs, at this point, may be tempted to outline their entire assessment and strategy just as they have worked it out. Often this will result in a too-lengthy report for the leadership attending to many other requirements. A better way to organize the leadership brief may be by using a chronology.

The first issues addressed are those that need to be accomplished before the deployment to the contingency location. These issues involve selection and standards for personnel to support the mission, immunizations and prophylactic medications that will be required, and PPE and other gear that may be required to mitigate disease or injury threats. It may also include a requirement for medical to be represented in advanced team reconnaissance missions that may precede the main group deployment. These are presented in a concise list with a clear message to the leadership that these are important issues and that the AMP, as the consultant to the leadership, is asking the leadership to require and enforce these as part of the overall mission policy.

The second issues addressed are those that need to be in place during the deployment. These issues involve travel limitations, billeting, clothing and uniforms, application of insect repellents, use of bed nets, compliance with prophylactic medications, interactions with the local population, food and water sources, and early reporting of illness and injury to the medical personnel. Again, the AMP must emphasize to the leadership that these are recommendations designed to mitigate against disease and injury threats, which will require leadership enforcement to succeed.

The third set of issues are those that will be required upon completion of the mission. Issues such as testing for latent TB infection, reporting of health status upon completion, and collection of medical records kept during the deployment may all fall into this category.

The final issue that should be part of the AMPs briefing to leadership includes the emergency response and evacuation plan. When activated, these plans will often require resources such as vehicles and aircraft, which are outside the direct control of the AMP. Therefore, it is vital that leadership knows what the plans are and what the requested resources might be in the various scenarios. Again, it is important at all stages that the AMP emphasizes that his/her recommendations will only be effective if they are endorsed and enforced by the leadership.

AIR MEDICAL TRANSPORT

As the AMP looks to emergency plans that require increasing acuity or higher echelons of care to which patients will be transferred, the capability to move patients by air quickly becomes an important issue. In fact, the need to care for patients in-flight is a unique and challenging environment in its own right. In this section, we will focus specifically on the broad range of air medical transport capabilities.

Introduction and Definitions

Air medical transport is the use of aircraft to rescue, move, and care for patients, and to support medical operations. Air medical missions are most often from the scene of injury or illness to a hospital, often called *scene missions*, or between hospitals, often called *interhospital missions*. The unique aircraft environment and its effects on the patients and crew must be considered during air medical operations. They cannot be the primary focus during missions or in the field of air medical transport research. Air medical transport research, instead, is focused on the care of patients in the aviation environment, with proper consideration for aeromedical issues along with other factors. Therefore, aerospace medicine and air medical transport overlap in some ways but can be considered two distinct fields.

The air ambulance is only part of air medical care. The vehicle and medical crew represent a sophisticated system of care that alters local medical capabilities. For example, the addition of an air ambulance to a regional health care system may allow development of a specialty care capability, such as a neonatal intensive care unit or a liver transplant service. It may also strengthen the ability of regional emergency medical service (EMS) systems to provide care for trauma, cardiac, or pediatric patients by providing high level out-of-hospital care over a broader geographic region than could previously be covered by ground vehicles. Physician medical direction is essential in the planning and operation of an air medical program, and is best provided by physicians trained and experienced in critical care transport medicine. The Air Medical Physician Association is one organization that provides a forum for training, support, and professional development of physicians involved in air medical transport (1). The Aerospace Medical Association provides a forum for those interested in advancing scientific knowledge regarding the health, safety, and performance of those involved in aerospace medicine (2).

History of Air Medical Transport

Shortly after aircraft technology progressed to the point that passengers could be flown, they were recognized as a means to move persons in distress. There is some debate about the first intentional patient transport by air, including the date and whether the aircraft was a balloon or a fixed-wing airplane (3). Regardless of the aircraft used, the history of air medicine is linked to military conflict. The helicopter was first widely and successfully used during the wars in Korea and Vietnam. It offered advantages of access in hostile terrain and rapid transport speed compared with ground alternatives (4). The helicopter developed significantly from an aviation perspective during the time between those two conflicts. The aircraft typically used during the Korean conflict for field rescue were light helicopters that carried the patient on externally mounted stretchers. Medical care was limited to measures before flight, because there was no access to the patient until landing.

By the Vietnam War, larger helicopters, such as the Huey, with interior cabins of sufficient size to fit stretchers and medical providers, were available, and patients were usually transported inside the aircraft. This allowed medical attention during transport. Dr. Spurgeon Neel, an Army flight surgeon, played an important role in the design and development of the Huey, assuring that air evacuation was in mind during the process. The helicopter rapidly became a favored aircraft for short-range patient rescue and transport in U.S. military operations, with 110 air ambulances in Vietnam performing more than 7,000 evacuations monthly by 1968, and approximately 900,000 total missions during the 11 years of operation in Vietnam (5,6). Similar military helicopter use continues, with helicopters figuring prominently in field medical care in subsequent conflicts and in current U.S. (and other) military deployments. During recent conflicts in Afghanistan and Iraq, helicopters were used to deliver patients to and from field hospitals such as those staffed by forward surgical teams (FSTs) and as a link between this immediate field care and secondary care on hospital ships or in support hospitals. Fixed-wing aircraft are used for longer distance patient transport and for logistic support. These missions include evacuation of injured soldiers to military medical centers in the United States and bases supporting troops in action.

Significant civilian application of helicopter medical care within the continental United States began as personnel experienced with military air medical helicopter operations returned from Vietnam during the 1960s and 1970s. They proposed that similar technology would be beneficial in the civilian environment, particularly for trauma victims (7). Other countries also developed air ambulance services, some focusing on emergent patient transport, some on delivery of medical resources to remote areas, and others on rescue.

Justification for Air Medical Transport

Common sense suggests that patients with survivable illness or injury can benefit from appropriate care delivered before arrival to a hospital setting if it can be done without excessive risk. In a hostile military situation, where medical capability may need to be somewhat distant from areas of likely injury and where other means of transport are not readily available (because of terrain or enemy threat), there are clear advantages to helicopter medical transport. Justification for use in the civilian environment is often less clear.

When considering this justification, there should be clear advantages to use of the aircraft system. This could either be due to the aircraft capabilities, the medical crew carried, or both. For example, many medical conditions worsen rapidly without prompt advanced care. Time saved, therefore, is a potential advantage of aircraft use, whether the aircraft brings the patient to a hospital capable of this care or brings skilled advanced care staff to the patient. In most systems, the air medical crew is highly skilled and trained, with extensive experience in critical care transport. Their expertise may not be available by ground because of time, distance, or area covered. Although their presence cannot replace the hospital, their advanced skills, experience, and equipment may provide a patient care advantage over care available from ground EMS resources. In fact, it is a requirement that the skill level of the air medical crew be at least as high as that of the responding EMS as it would not be appropriate to hand off care to a lesser capability. In many cases, the advantages of speed and access afforded by the aircraft are augmented by the medical crew capabilities; the patient benefits from both.

Unfortunately, these theoretic advantages of civilian air medical transport are often difficult to demonstrate objectively. Confounding factors include educational efforts for referral facilities, coordination with tertiary care hospitals for consultation before and during transport, increasing regionalization and specialization of health care, and continuing parallel advances in ground EMS and emergency medicine. All these factors are difficult to analytically separate from the effects of the air medical aircraft or crew alone. Early scientific analysis of helicopter medical care focused on trauma, with some consideration for cardiac, pediatric, and obstetric patients. Additional efforts included appropriateness of use, estimation of need, and clinical techniques during flight. Although a wealth of helicopter medical literature exists, rigorous appraisal of patient outcome benefit has been limited by sample size, the confounding variables noted earlier, and lack of concurrent control groups (8). There is less extensive literature evaluating fixed-wing air medical care and even less on long-distance ("repatriation") care during commercial airline flight.

Therefore, many air medical programs are established and others continue to operate based on anecdotal evidence of benefit. It should be stressed, however, that ground EMS systems, and many other aspects of medical care have no greater objective justification in terms of improved patient outcome or public health benefit than the evidence that exists to justify air medical care. The continued existence of civilian air medical rotary wing programs and the recent emergence of privately run for-profit programs providing similar service argue that there is at least a perceived benefit.

System Types

Many factors influence the design of air medical systems. Considerations begin with general safety and the specific system mission. Search-and-rescue (SAR) operations, for example, focus on finding and removing the victim from an endangering environment. The aircraft choice, equipment installed, crew selection and training for SAR missions will require a significantly different approach than a system designed for optimal interhospital patient transport. Efforts to develop platforms capable of multiple missions can add capability but may result in compromise. In many cases, platforms capable of interhospital and transfer and accident scene response can be developed logically, whereas SAR, mountain rescue, high-altitude operations, or rescue at sea missions require specific solutions. This chapter does not cover SAR operations in detail, and the reader is referred to specific texts on that subject (see **Recommended Readings**).

System configurations may be grouped based on the mission, type of aircraft used, medical team and resources, and availability. There are hundreds of part-time (the aircraft must be reconfigured from other uses such as executive transport) fixed-wing air medical programs that perform elective transport of stable patients as one of their primary missions using on-call medical crew. There are also many (~250 in the United States) full-time dedicated helicopter air medical programs. Many are small units utilizing one or two helicopters. Most are based at or supported by hospitals and staffed with medical professionals who work at those facilities. However, many are located strategically to provide rapid access to a geographic area at bases such as airports, fire stations, and so on. Physicians, nurses, paramedics, and respiratory therapists are the most common members of the air medical crew, with physician assistants, nurse practitioners, and other providers found in some systems.

Some systems offer both fixed-wing and helicopter service, and an increasing number coordinate with or directly provide ground ambulance transfer as well. Few civilian air medical systems in the United States focus on SAR operations, leaving that mission to the Coast Guard and other military/public service agencies. However, many U.S. programs perform limited search operations, and some train in regionally specific rescue, such as hover operations over water, snow, or wilderness terrain. In other countries, the rescue mission is often a component of civilian air medical systems, with winch lift and other rescue functions. Interfacility helicopter transport is increasingly common in non–U.S. programs.

A recent review showed the typical U.S. helicopter program performed approximately 800 patient missions annually over the last 5 years. Approximately one third of these missions transported the patient from the scene of accident or illness and two thirds moved between hospitals, with an average patient transport distance of 88 km (55 mi). Approximately one third of missions occurred at night. There has been a gradual trend toward increases in annual patients per program, transport distance, and overall flight hours in most regions of the United States during the last 5 years (9).

Standards

In the United States, civilian rotor-wing air medical programs predominantly transport patients from the scene of accident or illness to a hospital, or between hospitals. A small number of programs routinely participate in limited SAR operations, and an even smaller number see SAR as their primary mission. Fixed-wing programs transport between airports, with the patient being transported between hospitals in almost all cases. Exceptions include programs such as the Australian and African Flying Doctor Services, which operate mainly in remote rural or wilderness areas.

The Commission on Accreditation of Medical Transport Systems (CAMTS) is the predominant accrediting body for civilian rotor and fixed-wing transport systems in the United States (10). CAMTS has standards for basic life support (BLS), advanced life support (ALS), and specialty levels of care. These standards address safety, staff qualifications, communications, equipment, patient care, documentation, follow-up, quality assurance, and other aspects of air medical operations. The CAMTS Board of Directors accredits air medical transport programs after a satisfactory site inspection and review of extensive documentation to document compliance with applicable standards. CAMTS accreditation is recognized by many states and medical insurers, but is currently voluntary in most states. Because many air medical programs operate ground critical care transport services as well, CAMTS is also involved in accrediting this aspect of critical care transport, and has developed ground BLS standards for programs that provide this aspect of care along with critical care air and ground transport. Unlike military medical crew or crews on commercial airlines, the medical personnel on air medical aircraft are considered passengers and are not regulated as crewmembers by Federal Aviation Administration (FAA) standards or regulations.

In addition to CAMTS standards, air medical crews must also comply with state, regional, and/or local medical laws, regulations, and standards. In addition, hospitals and other health care facilities have internal credentialing standards, as do some reimbursement systems. These requirements vary widely, with few widespread standards. Although national certifications exist, they do not confer practice permission in specific jurisdictions. This situation causes potential conflict, with air medical providers potentially not licensed in the state, credentialed in the region, or accepted as a member of the hospital staff where they are caring for a patient. In other situations, air medical crew are trained in and perform procedures that are not within the allowed skill set for providers with similar credentials operating in ground EMS systems in the same region. Various solutions, from national medical licensing and practice credentialing to invoking the theory of mutual aid to imply "temporary credentials" for providers without local credentials have been applied to resolve this practice conflict.

Aircraft and Aviation Equipment

Most helicopters involved in air medical operations are dedicated to the purpose. Specific aircraft model, interior design, and equipment choice follow the intent to provide medical care. The most commonly used aircraft models are small and midsized twin-engine and midsized single-engine aircraft (11).

These helicopters are generally turbine powered, with the proportion of twin-engine aircraft relative to single-engine aircraft steadily increasing. Several manufacturers have introduced models in the last few years that claim design to specifically accommodate air medical needs. Cruising speeds of 160 to 257 km/hr (100–160 mi/hr) with ranges of 520 to 885 km (325–550 mi), a useful payload of 680 to 1,360 kg (1,500–3,000 lb), and service ceilings of 3,962 to 6,090 m (13,000–20,000 ft) are characteristic of these light midsized helicopters.

Instrument flight rules (IFR) flight is possible in many of these helicopters, but the need to avoid icing conditions and to fly between or near airports capable of instrument approaches limit the usefulness of IFR helicopter flight for air medical care. Recent availability of IFR flight using the global positioning satellite (GPS) system has expanded air medical IFR capabilities in some areas, but concerns regarding decreased safety with poor visibility operations continue to be validated by aircraft accidents in such weather conditions. Most air medical helicopters are certified for single pilot operation, many for single-pilot IFR operation and most air medical programs staff the aircraft with a single pilot. Some programs use two pilots during known IFR conditions. In some cases, particularly with smaller helicopter models, the patient area occupies cockpit space, prohibiting dual pilot operations. In comparison, many U.S. military helicopters of similar or slightly larger size and complexity are flown with two pilots in all conditions.

Helicopters are delicate machines and require significant preventive maintenance. Certified mechanics are required, and one mechanic per aircraft is not unusual in air medical operations. Spare aircraft are often provided on an as-needed basis from the aviation vendor or other lease source during prolonged maintenance.

The fixed-wing aircraft used for civilian air medical care are typically midsized twin-engine propeller or jet aircraft. They are typically capable of IFR operations, cruise at 399 to 644 km/hr (200–400 mi/hr) for ranges of 1,610 to 3,220 km (1,000–2,000 mi) with useful payloads of 907 to 3.175 kg (2,000–7,000 lb). With the capability to climb higher than helicopters to altitudes of 7,620 to 9,144 m (25,000–30,000 ft) with pressurized cabins when necessary, these aircraft can fly over inclement weather. These characteristics make fixed-wing aircraft most useful for missions greater than 241 to 322 km (150–200 mi) in distance where the additional delay required for airport–hospital transportation at either end becomes less significant. In addition, the useful load and altitude characteristics increase the margin of safety for operating these aircraft in hot or mountainous areas. Additional operational issues more commonly encountered in the fixed wing than the rotary wing environment include crossing regional or national boundaries, extended flight over water or remote terrain.

Currently under development are tilt-rotor aircraft with a blend of fixed-wing and helicopter capabilities. Although not currently in civilian use for air medical operations, when safe and reliable tilt-rotor aircraft are available, they will be potentially the best solution for many air medical programs operating in semirural or rural areas, in areas with frequent IFR weather, in areas with mountainous terrain, and for programs that transport specialty care teams requiring multiple providers or heavy equipment.

Personnel

Almost all dedicated helicopter air medical programs provide two crewmembers trained and dedicated to patient care, with one or two pilots. An effort is made at most programs to isolate the pilots from medical care and decisions to avoid distracting them from objective aviation judgment. A variety of certifications form the basic medical crew qualifications, including physician, nurse, paramedic, and respiratory therapist. Additional training to ensure familiarity with the aircraft and flight environment and advanced medical skills particular to the programs mission is required in many cases, blurring the distinction between provider types. It has been suggested that there is no "best" crew mix aboard an air medical helicopter, so long as the providers have the knowledge, judgment, and teamwork skills necessary to perform the mission. There has been discussion of certification as basic or advanced air medical crew, or as a medical director, with multiple professional backgrounds acceptable as a prerequisite, but these discussions are preliminary. The Air Medical Physician Association, the National Association of EMS Physicians, and other professional organizations involved in air medical transport are the forum for these discussions. (www.AMPA.org, www.NAEMSP.org)

Pilots, Mechanics, and Aviation Personnel

Many helicopter air medical programs are hospital-based. The hospital usually provides the medical crew and physical facilities for the program, while leasing the aircraft, pilots, mechanics, and aviation support from an aviation vendor. A minority of programs choose to operate independently, acting as FAA Part 135 operators in the United States. These programs purchase or lease their own aircraft, and hire the entire staff, including aviation personnel. Some aviation vendors have begun to offer a variety of other support services, ranging from communications and dispatch to total operation of the air medical program, including hiring the medical crew, thereby blurring former medical/aviation role separations. During recent years, this range of program configuration has allowed a variety of different schemes to develop and flourish, satisfying particular regional or institutional needs.

In fixed-wing programs, pilots and mechanics are typically based at an airport, as is the airplane. In many cases, the aviation aspect of such operations is subcontracted to an outside vendor. Therefore, they often have little direct interaction with the health care providers and facility that sponsors their program. Their focus on the aviation aspect of the program may provide a flying safety advantage, but this must be balanced against a reduced understanding of the medical needs of the providers and patient.

Medical Crew

Medical care during flight is provided in an environment that is fundamentally different from that in a hospital or even during ground transport. As such, it requires specialized crew and specialized physician oversight. Noise, vibration, restricted physical space, motion, altitude changes, temperature extremes, and time without access to other resources are all factors that can profoundly influence patient care. For example, glass intravenous bottles, air-filled balloons in splints or tube cuffs are potentially dangerous and unsuitable for air medical transport. Trapped gas in the patient (or crew) whether that found normally (middle ear, sinus, bowel, etc.) or due to medical condition (pneumothorax, pneumoperitoneum, pneumoencephalos, tooth abscess, etc.), can create potentially life-threatening problems with changes in altitude. Patient and crew restraint with seat belt–type systems are essential for safety in flight, but often restrict access to the patient or medical equipment.

Some medical therapies are difficult to provide during transport, including traction on long bone fractures using hanging weights, low-pressure patient bedding to avoid or treat skin breakdown, and treatments requiring large external devices such as renal dialysis, balloon counterpulsation, or cardiopulmonary bypass. Medications and medical devices chosen for inclusion as routine equipment on air medical systems should be judged according to need, frequency of use, and ability to function as designed in the environment (temperature, vibration, weight, size, shelf life, and need for power, risk of use or malfunction, potential effects of electromagnetic radiation on avionics, etc.). If a particular therapy is judged beneficial and commonly used, a means can usually be devised to provide it during flight. In some cases, this has required alteration or even complete redesign of the device.

Overcoming these challenges requires creative and flexible thinking. Well-trained and experienced professionals make the best vehicle and equipment choices. The system physician consultant and medical aircrew must balance the clinical benefits of the aviation environment for each patient against the risks, and decide on the appropriateness of the transport mode. In order to make these decisions, the air medical crew and physicians overseeing the system must have basic training in and understanding of aerospace medicine issues such as altitude physiology and the effects of motion in flight.

The medical crew on fixed-wing transport varies markedly. In some cases, the patient is stable and requires minimal medical attention (e.g., patient is bedridden but otherwise healthy, requires oxygen during transport) and the transport is justified based on distance and medical condition that precludes commercial transport. However, in other cases, patients transported by fixed-wing aircraft are as ill as those transported by helicopter and are out of hospital for a longer time. These patients can be extremely challenging and deserve a high level of monitoring and care. Because fixed-wing aircraft can generally carry greater loads than helicopters and have more interior room, additional crew or medical equipment can be accommodated. If borders are crossed, it may be necessary for the crew to arrange licenses, permits, and other papers in order to provide care, carry or administer medication such as narcotics across international borders, and provide intermediate transport.

Communications Systems

Radios are used to communicate with the helicopter crew and between the aircraft and ground medical providers. This requires installation of frequency-agile radios and crew knowledge of radio operations, as well as education for ground EMS/public safety providers and hospital personnel. Fixed-wing aircraft typically land at airports and therefore have little need for EMS radios. Cellular telephones offer advantages in some situations, but operation during flight is limited under current U.S. Federal Communications Commission regulations. However, specific in-flight telephone equipment is becoming increasingly affordable, and is installed in many aircraft.

Medical crew must successfully integrate telemedicine principles into their practice. Medical crews require and provide vital information from the sending and receiving personnel respectively. Ideally, they should be able to rapidly discuss their patient and provide updates on patient condition throughout the transport. It can be critical to the survival of the patient that the receiving institution has the necessary information to insure that appropriate equipment and personnel are available to receive their patient and provide necessary care. Communication using radios, wireless telephones, and computer devices is an essential component of practice for air medical crew.

Medical Equipment

Medical equipment varies with the mission, but should include, at a minimum, a means to secure the patient safely, monitor his or her condition, and deliver indicated therapy. The nature of the equipment onboard, as well as the medical personnel will define the ''acuity level'' of the aircraft. Adult patients are typically transported on a stretcher or spinal immobilization device, with pediatric and neonatal patients requiring size-adjusted equipment. Incubators are often mounted on stretchers for neonatal missions.

In addition to close clinical observation, patient monitors on ALS or specialty level aircraft typically include monitoring of cardiac rhythm, pulse rate, blood pressure, and oxygen saturation. Additional monitors (temperature, venous pressure, arterial pressure and waveform, end-tidal CO_2, and others) are used in some situations. Automated or amplified equipment is typically used due to the noise level and vibration present in the aircraft, with Doppler stethoscopes in common use. Active noise-cancelling headphones and stethoscopes are used in some situations. As previously discussed, all equipment must be properly selected for safe aircraft use, tested for the ability to function in the anticipated flight environment, and securely mounted for use in the air medical environment.

Typical Operations

Typical helicopter operations are limited by the range of the aircraft, terrain, weather, and program mission. In most cases, a local service area is designated within a limited radius (e.g., 40–56 km, 25–35 mi) of the program base. This area contains frequent patient referral sites and gives the pilots an opportunity for detailed terrain and weather pattern familiarization.

Patient care during transport must take into account the environmental, medical, and temporal factors involved. Decisions to provide or withhold therapy, for example, must be considered in light of the time needed to apply the therapy, the expected benefit, and the time remaining in the transport until therapy could be provided in a more traditional care environment. With limited crew available, potentially life-saving treatments must be given priority whereas therapy judged as ''optional'' can wait until the transport is completed. This is particularly true if these treatments could potentially lengthen the transport time.

Similar decisions must be made by the referring care providers. In most cases, the air medical transport is initiated because capabilities of the referring facility or ambulance service are exceeded by actual or anticipated patient needs. These situations may vary from the patient still trapped in a car crash who is unstable and/or distant from definitive care to the hospitalized patient with understood but critical conditions in need of care that exceeds that of the facility. The ''at-scene'' patient may be referred due to potential for crisis and need for rapid evaluation, whereas the hospital patient is referred due to known illness in need of rapid treatment.

In either case, the air medical team will enter and operate in a stressful environment. Additionally, the air medical team is typically a scarce resource within a specific region. This can force the need to triage multiple valid requests within this stressful environment. An organized communications system with committed medical direction and professional communications specialists is necessary for logistic support and optimal application of the air medical resource. In addition, unless referral patterns result in frequent visits to the same referring facility or crash scenes, the air medical team is often entering a physically unfamiliar environment. Professional management of patient care and interpersonal relations in the face of these challenges calls for exceptional medical and human skill.

Actual patient care by the air medical team often begins with the request for care and transport. Consultative discussions often alter patient care at the referral hospital, and the receiving hospital often begins preparation for patient care long before actual patient arrival. These measures alone may speed needed care and may begin before the actual transport. Most air medical teams prefer to arrive at the patient bedside when transferring a patient rather than meet the patient at a hospital helipad. The need to transfer medications and monitoring devices, review medical information and secure records (including radiographs), and occasionally perform procedures makes an outdoors transfer of care to the medical team suboptimal in most cases. However, thorough communication should inform the team about their patient before arrival at the bedside. With training, equipment, and experience, it may be possible to reduce the patient turnover time.

Once the air medical team has begun care, they must move the patient to the air medical transport stretcher and attach monitoring and care devices. Only with training, practice, and careful effort can the team insure intravenous lines, endotracheal and other tubes, monitors and other equipment remain attached during patient movement to the stretcher and transfer to the aircraft. Most currently used medical devices were not specifically designed to accommodate movement from one stretcher to another or from one vehicle to another. Current efforts to design advanced-capability stretchers with safe and effective monitor mounts may improve this situation.

The air medical crew may be required to attach additional monitoring equipment to substitute for more routine assessment techniques that are not effective in the cramped and noisy environment in the aircraft. In other cases, the air medical crew may need to detach or "cap off" some monitors that cannot be used during the transport. These might include central venous pressure monitors, arterial pressure monitors, and intracranial pressure monitors. They must do this in such a way that they remain patent during transfer. With education, the referring staff can understand the constraints of the aircraft environment and prepare the patient for transport more fully before the transport team arrives.

In civilian situations, procedures such as securing the airway, obtaining intravenous access, attaching monitoring devices, gastric decompression, splinting, pneumothorax decompression, and patient restraint are typically best performed before takeoff. If such procedures are performed in flight, practice and thoughtful protocols and specific situation training scenarios are necessary to adapt ground skills to the aviation environment. For example, auscultation to confirm nasogastric tube placement is challenging in flight with standard stethoscopes. Active noise-cancelling equipment or Doppler stethoscopes can be substituted, but these devices must be available in the aircraft and still do not equal a quiet, controlled setting. In the future, larger aircraft with redesign in the patient care area may improve access to the patient and enhance the ability to perform more procedures safely during flight. Additional efforts are now under way to improve in flight diagnostic capability including ultrasonographic examinations and blood analysis.

Aside from insuring that the patient receives necessary medical care, the air medical care team must consider profound affects of the unique aviation environment. Altitude changes are not typically excessive in helicopter operations where flight altitudes are 300 to 600 m (1,000–2,000 ft) above ground. However, in mountainous areas it may be necessary to climb or descend significantly to clear terrain and/or access patients. In IFR conditions, flight plans may call for significant altitude changes to clear bad weather. In these cases, the effects of altitude change may be significant, and care must be adjusted to account for them. Any gas-containing medical devices such as tube balloons and inflated splints must be pressure-adjusted or better yet, filled with liquid. Trapped gas, as discussed earlier, must be recognized and the condition addressed before safe flight may be considered.

Fixed-wing operations are more typically engaged in moving patients between fixed care facilities. As such, most operate in a less emergent, and therefore have more time to plan missions, assemble optimal crewmembers, and in many cases assure reimbursement before takeoff. Some flights are simply aimed at moving patients to a geographically preferable location. Others may be to enable the patient to receive specialized care not available near the referring hospital. Either situation allows greater efforts to insure a stable patient, which can be performed by referring medical personnel. However, these efforts must still often be balanced against the delay of transfer. For example, the time required to perform diagnostic testing such as computed tomography scan, cross-match blood or other blood products, or obtain vascular access for central venous pressure monitoring must be balanced against the expected transport time and consequences of delay in therapy. Depending on the situation, the advantages of additional treatment at the referring facility may be offset by the delay to treatment at the receiving facility.

Even in situations where the patient is optimally stabilized, patient deterioration may occur during transport. The judgment of a professional air medical crew is vital. They must have the skills necessary to monitor a patient during lengthy transports. They must understand when they require physician medical direction, provided off-line through protocols or on-line by radio or cell phone. In addition, they must have the skills to provide stabilization *en route*. Although providers with other levels of training can perform a variety of advanced patient care skills, physician experience, training, and judgment are most beneficial.

Commercial airlines are able to accommodate many patients with minor medical problems, particularly if adequate time for planning is allowed. Extra seat purchase, companion medical personnel, oxygen, and similar issues must be arranged days in advance of the flight. Individual airline policies vary, and their medical directors guide these policies. The Aerospace Medical Association has published guidelines for airline travel (12). In addition to special consideration during the flight, transport and care to and from the airport and through airport facilities may be necessary.

CURRENT ISSUES

Safety

Helicopter and fixed-wing aircraft flights are safer on an accident-per-passenger-mile basis than similar ground transport in an ambulance. In fact, the rate of ground ambulance accidents is approximately 10 times higher than the air medical helicopter rate (13). However, aviation conditions are less forgiving and therefore aircraft accidents tend to be more serious. Despite many aviation advances including new helicopter models, GPS navigation, radar altimeters, and computerized weather systems intended to improve the safety of flight, far too many medical helicopters and airplanes crash each year.

In the 1980s, civilian air medical helicopter crashes in the United States occurred at a rate that alarmed the industry. The U.S. National Transportation Safety Board (NTSB) released a report in 1988 that reviewed 59 civilian air medical crashes that occurred between 1978 and 1986. There were 53 fatalities caused by these crashes. An accident rate of 12.34 accidents per 100,000 flight hours and a fatal accident rate of 5.40 per

100,000 flight hours between 1980 and 1985 were reported. Both rates were significantly higher than nonmedical civilian helicopter accident rates.

This data led to significant safety of flight efforts including the implementation of FAA judgment training programs, landing zone educational programs, and safety awareness training among all members of the crew. These programs were successful and that rate declined. In 1991 there was an accident rate of 3.1/100,000 transports, or 2.98/100,000 hr, with each transport averaging about one flight hour. The industry once went more than 12 months without an accident during the early 1990s. Unfortunately, the accident rate increased during the late 1990s. In 1998, there were 8 accidents, in 1999, there were 10, and in 2000, there were 12 air medical accidents. However, there was also a significant increase in the number of helicopters flying civilian air medical missions in the United States during these years. Overall, the accident rate increased from 0.56 accidents per 100,000 flight hours in 1996 to 6.79 in 2000. However, the fatal accident rate during the same period stayed between 1.52 and 2.09 fatal accidents per 100,000 flight hours. This is less than half the fatal accident rate seen in the early 1980s, and has been sustained for more than 8 years.

Air medical helicopter accidents occur about equally during day or night missions. Approximately one third of overall missions occur at night, so the accident rate is significantly higher at night. Approximately one third of accidents occur *en route*, and two thirds during takeoff or landing. Overall, air medical helicopters crash at approximately three times the rate of non-EMS helicopters and the fatality rate in air medical crashes tends to be higher as well. This difference has been attributed to a variety of factors, including the immediacy and uncertainty of flights, inadequate aircraft systems, poor landing zone familiarity, and the frequent need to land at unimproved sites such as agricultural and sports fields.

Pilot fatigue is often cited as a factor in these accidents. However, one review of air medical helicopter accidents showed they were not clustered at the end of shifts, late at night, or in other patterns that might suggest fatigue as a factor. Furthermore, FAA crew rest requirements for pilots are the same for EMS flyers as they are for any other pilot. Of note, these are not matched by rest requirements for most medical care providers. Regardless of the root cause, approximately 70% of air medical accidents are attributed to pilot error, with weather and object collision most often cited as secondary factors.

In terms of survivability, a review of factors associated with occupant survival showed that interior modifications designed to enhance patient care access and capability likely increase the risk of injury in the case of a mishap. This is likely due to several features. First, settings that allow better access to the patient often compromise the proper use of restraint systems and load-absorbing seats. Placement of equipment where it is easy to access the patient may intrude into the head strike area. Finally, efforts to insure equipment is readily available may translate into loose equipment which can be thrown around and cause injury in the case of a crash (14).

Twin-engine helicopters are often touted as safer than single-engine helicopters because the redundancy of systems theoretically reduces the risk of accident from engine failure. However, because so few accidents overall are caused by engine failure, it is difficult to prove that twin-engine helicopters are safer. In fact, the additional cost of twin-engine aircraft may be better spent on pilot training, program measures to improve judgment and increased maintenance. Helicopters are complex machines requiring frequent preventive maintenance and inspection. However, few hospital-based helicopter air medical programs provide hangar facilities for this required maintenance. Inspections and most routine maintenance are typically performed outdoors, day and night, often from a ladder or while balancing on small steps built into the side of the aircraft. This practice forces mechanics to work in an environment that is not conducive to careful scrutiny. This lack of basic aviation facilities is much less of an issue for fixed-wing programs operating from airports with hanger facilities. Despite these difficulties, mechanical accidents are rare which reflects well on the mechanics involved in maintaining these aircraft. Still, the addition of protected, climate controlled and well-lit maintenance facilities could only make their job easier and the industry safer.

The vast majority of mishaps are attributed to human error. Investigation by the NTSB and other agencies shows approximately 90% of medical helicopter accidents can be attributed to errors in judgment. The most common of these is continued flight into deteriorating weather with subsequent failure to follow IFR procedures. Human error chains may begin with program design and extend through aircraft maintenance and crew training procedures. Equipment choices, administrative attitude issues, the dispatch process, and mission acceptance can all contribute to errors in judgment. In the United States, both military aviation and the FAA have promoted judgment training, crew resource management (CRM), and various other efforts to reduce human errors and thereby break the chain of errors that can lead to a crash. These efforts have had some success, but the continued unacceptable crash rate must be addressed anew if the air medical industry is to provide care in the future (15).

Logistic support for air medical programs can be provided in several ways. Often it is provided by the hospital, which buys or leases aircraft and hires personnel. In other cases, the program is managed by a government agency tasked with providing the service to a particular region. In other cases, a for-profit aviation vendor provides the service. Regardless of the source of support, the sponsoring institution must insure adequate resources for proper maintenance, adequate facilities, personnel training, and other aviation services necessary to operate the program safely. Even for those programs that subcontract aspects of aviation operations require an understanding of aviation operations necessary to avoid mistakes such as inadequate maintenance facilities, hiring unqualified personnel, or other measures that may reduce immediate costs but risk long-term problems.

The most effective way to avoid crashes is to break an error chain. This is done by identifying and correcting the initial errors in the chain before they result in a catastrophic error. In clinical situations, errors can be reduced through care monitoring by expert practitioners. For example, an experienced attending physician observing a procedure performed by a medical student is likely to be able to reduce procedural error, and educate the student as well. In the air medical environment, the medical crew and dispatch staff may be able to provide some feedback to the pilot, and the reverse may occur regarding medical issues. Although familiarity may facilitate feedback at a basic level, the presence of a second expert pilot may be helpful in "trapping" and correcting pilot judgment errors that would not be noticed by nonpilot crew. However, there is no assurance that the same circumstances that led one pilot astray (marginal weather, time pressure, etc.) will not similarly affect a second pilot, and some suggest that trained nonpilot observers (the medical crew and communications personnel) can act as an adequate error-trapping mechanism. In addition, there are group error modes that may come into play with additional personnel involved in decisions, and these must be controlled as well (15).

Competition

In the United States, health care is often delivered in a competitive environment. Even nonprofit hospitals compete for market share, specialty patients, and prestige. An air medical program can be an important part of the hospital's marketing effort, both directly and indirectly. Direct benefits accrue from the ability to transfer patients into the hospital from afar. Professional and polite air medical crew can impress referring staff, further improving the reputation of the hospital. Other indirect benefits include the positive overall impression patients have of a hospital that provides helicopter or other critical care transport services. This competitive atmosphere may involve the air medical program. Although competition in a free market is somewhat at the heart of capitalism, competition between neighboring air medical programs is difficult to fully understand given the complexities of health care economics and the imperative to deliver the best possible patient care.

Because helicopter programs are scarce resources and often have overlapping service areas, one would expect a significant degree of mutual aid and support. Although this is true in much of the United States, there are areas of the country where requests for service are not referred for mutual aid when the requested program is busy, where helicopters overfly the nearest trauma center in favor of their base hospital, and where the level of competition may be detrimental to patient care. An example of excellent regional cooperation is found in the northeastern United States, where the North East Air Alliance, a group formed by the region's helicopter programs, meets regularly to establish mutual aid and disaster response protocols. Fixed-wing programs, due to the extended range of their aircraft, significantly overlap one another in service area. Therefore, quality of service, attitude of staff, and cost become important considerations when promoting a program. However, because of the relatively lower frequency of use of fixed-wing programs by individual hospitals, physicians, or EMS agencies, it is more difficult for these programs to establish and maintain a reputation for quality through actual experience in a given region.

As the economics of U.S. health care grow increasingly complex, a challenge for air medical programs is the maintenance of safe service in an increasingly competitive medical environment without stooping to overly competitive air medical operations that jeopardize the excellence of patient care.

Medical Benefit

A current issue linked to competition and economics is the issue of medical benefit. Individual case reports of life-saving care exist, and the cost per year of life saved for a helicopter program compares favorably with other "expensive" medical therapies, but there is no generally accepted literature that proves the overall benefit of helicopter or fixed-wing air medical care systems in terms related to patient outcome. Studies are challenging because of sample size limits, confounding factors, and issues related to consent in the prehospital environment. Indirect measures, such as hospital discharge outcomes for flown versus ground-arriving patients, may be the best available data, but are similarly limited. The appropriate use of helicopter transport has been reviewed by third-party payers and by regulatory bodies, including the Massachusetts Department of Health (16) and most recently the Centers for Medicare and Medicaid Services (CMS, formerly HCFA). The Massachusetts Utilization Review process found an overwhelming number of helicopter transports medically appropriate. The recently adopted CMS ambulance reimbursement guidelines provide reimbursement for appropriate use of air ambulances at a level well above that for ground ambulances (17). These treatments may be assumed to be a validation of medical benefit, but remain a very indirect measure of utility. This problem remains a challenge for EMS in general, and air medical care in particular. Efforts to quantify the number of lives saved and morbidity averted are needed to justify the medical benefit of air medical transport in many situations.

The medical appropriateness of fixed-wing transport is determined by both patient choice and objective measures. In many cases, fixed-wing transport is used for convenience or clearly indicated access to advanced care. For example, a patient may wish to be flown to a hospital closer to home after an accident while on holiday, or may be in an area of the world without tertiary care medical resources and seek transport for these services. The objective absence of certain services in a region (neurosurgery, orthopedic care, etc.) simplifies verification of medical benefit in these situations. In many cases, typical health insurance plans do not cover fixed-wing transport; therefore, special insurance programs or patient payment is required. Helicopter emergency transport is more frequently covered by health insurance, but not universally. The medical benefit of transport must be certified by a physician in many cases before reimbursement is authorized.

Cost

The cost of air medical care can be examined from many perspectives. For example, the bill for a helicopter or fixed-wing patient transfer can be compared with a similar transfer by ground. Alternatively, the overall cost of the helicopter or fixed-wing system can be compared with the cost of a similarly functional ground system. Another model is to estimate the replacement value of an air medical program. Replacement value is an economic concept where the studied entity is theoretically replaced by other technology, and the cost of the replacement technology calculated to provide an estimate of the studied entity's value. For example, a helicopter ambulance could be replaced by a system of ground ambulances strategically deployed to provide an equal level medical crew with similar response time to requesting agencies. One analysis using this model demonstrated a significant cost savings using a helicopter to replace ground critical care ambulances (13). Other examinations are possible.

From many of these perspectives, an air medical transport costs more than a ground transport. This may be an oversimplification. It is true that a helicopter or jet costs more than a truck to purchase, maintain, fuel, and insure. However, a single helicopter can provide timely care over a much larger area than a single ground ambulance if requests for care come at a reasonable rate and weather is favorable. In some cases, such as remote and island communities, or even places with episodic heavy traffic, the helicopter provides the only rapid means of transporting a critical patient. Fixed-wing aircraft similarly provide capabilities that are either impossible or absurd with ground vehicles, such as rapid transport of patients across continents or retrieval of patients across large bodies of water.

Military services also have budget issues, and funding cuts severely reduced the budget available to the U.S. Coast Guard for air medical/SAR operations. These cuts forced closure of some stations and reduced the number of aircraft available in some areas, increasing response time. However, after the 2001 9/11 terrorist attacks, much of this funding was restored. Advances in SAR or medical capabilities [e.g., self-contained underwater breathing apparatus (scuba) or paramedic training for rescue swimmers] also have been limited by budget reductions. In some areas of the United States, civilian and other governmental agencies have assumed many roles formerly accommodated by the Coast Guard including boat rescue and medical support, but air medical and SAR operations are not as easily enhanced by civilian alternatives due to differences in training, equipment, and mission focus.

Owing to the indirect marketing benefits noted in the preceding text, many medical programs are heavily subsidized by their sponsors. For example, some of these services send bills at "ground rates" to avoid the appearance of competition. In other situations, the decision has been made to bill at a rate that offsets the cost of service, but the complexities of hospital accounting make it difficult to determine both cost and payment amounts. The air medical crew may provide services to other areas of the hospital without reimbursement, and may benefit from hospital services (such as accounting, supply, office, utilities, etc.) without paying for them. Insurance payments are often rolled into hospital bills, and do not itemize the air medical portion of the bill. This leads to difficulty in estimating air medical budgets. Stand-alone air medical programs exist, and many are able to operate with a profit margin. These programs can provide budget and operational benchmarks for the remainder of the industry, provided they are operated safely and efficiently. Insurers need to understand the absolute and relative indications for air medical care, and agree to reasonable compensation for service availability, the cost of operation, and safe program administration.

Disaster Response

Air medical assets can have a positive impact during disasters of all origins and magnitudes, greatly expanding the physical and technical resources available to local and regional disaster planners. However, there are limitations that must be recognized. Aircraft should be used to perform tasks that are better suited for aircraft than ground-based resources, and not for tasks that could be effectively performed by ground vehicles. For example, helicopters may be the sole means of rescue in some situations. In 2005, helicopters and fixed-wing aircraft rescued and transported thousands of victims of the U.S. Hurricane Katrina, demonstrating the effective use of air medical transport and aviation support to a disaster. This response, which included more than 60 civilian air medical helicopters and hundreds of military rotary and fixed-wing aircraft, is credited with saving many lives and providing other essential support. Before this incident, planning for such a large-scale relocation and application of civilian air medical assets had not occurred in the United States. The success of the Katrina/Rita response suggests that similar efforts could be coordinated for future needs.

In addition to patient transport, aircraft can be used to support logistics, reconnaissance, communications, and other disaster support missions. They can deliver disaster response and security personnel and supplies to areas that would be otherwise inaccessible. These capabilities should be planned and deployed through an integrated command structure so that missions are as safe and effective as possible.

Weather is the primary factor limiting aircraft response in disasters. High winds, low visibility, and icing conditions may prevail in the conditions that caused the disaster. Additional challenges include payload limits, availability of fuel and maintenance requirements. Regional disaster response plans that include air medical resources should consider these challenges and plan to provide solutions that will optimize use of aircraft to support disaster operations.

Military Transport

The movement of patients by air began with military efforts to move casualties from the battlefield. Patient movement continues to be an important military aviation capability supported with significant resources. Military air medical transport can be divided into the same search and rescue, scene and interfacility transport missions as their civilian counterparts. However, military air transport operations may occur in hostile territory with threats of weapons and explosives, they may occur during IFR weather, and may be performed by aircraft of opportunity rather than airframes dedicated to patient transport. In addition, a significant portion of military flight occurs in training mode, whereas civilian operations rarely simulate patient missions. These differences lead to an increased emphasis on avionics in military aircraft, a dual pilot configuration in almost all airframes used for patient transport, increased training, and frequent use of technologies such as night vision equipment and coordination with other aircraft not routinely available or used in the civilian environment.

There is a wide spectrum of medical capability within military mission. Perhaps the simplest and most recognizable military patient movement platform is the classic Army "dust-off" helicopter. Typically referred to as *medical evacuation* (MEDEVAC), this is usually an H-60 Black Hawk helicopter flown by a crew of four with a single emergency medical technician (EMT)-basic trained medic. There are numerous other military medical platforms that provide casualty evacuation (CASEVAC) for particular units or missions. Many of these have more highly trained medics with more sophisticated equipment. The medics on these flights are often paramedic trained and some are among the only nonphysicians to be advanced trauma life support (ATLS) certified. They fly a variety of aircraft including MH-60 Pavehawks, MH-53 Pavelows, and MH-47 Special Operations Aircraft to provide combat search and rescue as well as direct action medical support. Many of the medical teams that support this mission have advanced capability including advanced monitoring, ventilators, suction, and transfusion capability. They bring tremendous medical capability to the far forward battlefield and are indispensable in the modern combat environment.

Closer to home, coastal rescue is often performed by the U.S. Coast Guard, flying midsize twin-engine aircraft staffed by two highly skilled pilots, rescue swimmers, and other technical crew. The emphasis is on rescue, not advanced medical care. Basic EMS equipment and semiautomatic defibrillators are often available to these teams, with basic EMT-level training typical for those providing medical care. Occasionally, providers with higher level EMS training (military corpsman or other) are present on these missions. The epidemiology of coastal marine EMS reduces the need for ALS equipment or personnel, however (18). These teams are highly skilled at their rescue mission, and are highly regarded. Their aviation safety record is superb and stands as a model for the civilian sector.

Fixed-wing aeromedical evacuation (AE) is a major operational competency of the U.S. Air Force Medical Service. Aircraft with AE crews have been transporting stable, sick, and injured patients since World War II. The nurses and technicians that comprise the AE crews undergo special training and are skilled at configuring any cargo aircraft in the U.S. Air Force inventory for the AE mission. Tactical AE missions are flown within the theater of operations and are generally short-duration missions, 1 to 2 hours in length. Typically, the missions are flown on the C-130 Hercules cargo aircraft. Strategic AE missions are those that are flown to points outside the local theater of operations. These missions may last 6 to 8 hours or longer and are typically flown on larger jet aircraft such as the C-17 Globemaster III cargo aircraft.

From World War II through the Gulf War, the general practice among the branches of the U.S. military was to deploy large field hospitals with considerable holding capacity. Stabilization, surgical, and even rehabilitation care would be provided in theater. By the time a casualty was being transported, they were generally stable, requiring only routine nursing care. As operations became smaller and more expeditionary, the ability to deploy large medical capabilities became limited and the need to transport critically ill and injured patients after basic trauma stabilization became a necessity. Army FSTs Marine Forward Resuscitative Surgery Suites (FRSSs) and Air Force Mobile Forward Surgical Teams (MFSTs) were developed to bring surgical care closer to the point of injury (19). Following procedures to achieve rapid airway control, to halt bleeding and fecal contamination and to stabilize fractures, casualties are moved rapidly to the next level of care often requiring long evacuation distances.

Critical Care Transport

This change in operational concept required that patients who had been "stabilized" but were not yet "stable" by older aeroevacuation definitions be moved long distances by air. Beginning in the 1980s and early 1990s when critically injured or ill patients required air transport out of theater, physicians and nurses would be utilized from the forward deployed location to return with the patients as critical care medical attendants. This created a situation in which health care providers were asked to provide critical care in an aeromedical environment in which they had no specific training. Also problematic, the advanced medical equipment such as ventilators, monitors, and suction necessary to complete the missions was frequently not approved for flight. Finally, the forward deployed medical facilities lost those critical care personnel for the time necessary to move the patient and then find transport back. This could sometimes be a week or longer leaving the facility understaffed and vulnerable.

The U.S. Air Force, which has the responsibility for fixed-wing AE, transformed its capability in support of this evolution in military medical doctrine. Critical Care Air Transport Team (CCATT) were developed by the U.S. Air Force beginning in 1994 (20) and the teams have augmented standard AE crews since that time. These teams now make it possible to move stabilized but still critically ill and injured casualties on a regular basis. As a result, the present military casualty may undergo two or more surgical procedures and be back in the continental United States in 72 hours or less to begin their definitive care and rehabilitation.

This evolution in medical doctrine has resulted in a remarkable improvement in the lethality of war wounds rate. According to the Department of Defense, this rate was 30% during World War II, 25% during the Korean War, and 24% during the Vietnam War and the first Persian Gulf War in 1991. During the conflicts in Afghanistan and Iraq, the rate has been reduced to well below 10% (21).

U.S. Air Force critical care air transport teams (CCATT) consist of three medical personnel. Team members include a critical care physician, typically one specializing in pulmonary/critical care, emergency medicine, anesthesiology, or surgery, a critical care nurse, and a cardiopulmonary technician. Most importantly, these individuals are actively engaged in the care of critically ill and injured patients in their everyday practice. At the time of initial assignment to CCATT, team members attend initial training in an intensive 2-week course that prepares team members to apply the critical care competencies they already have in the aeromedical environment. Before actual deployment, CCATT members attend an additional 2 weeks of training to further enhance their critical care skills (20,22).

CCATTs are outfitted with the equipment and supplies needed to provide critical care for three to six patients depending on the level of patient acuity. This amounts to approximately 600 lb of equipment and supplies that are divided up into eight man-portable packs that are taken on each mission. Should a particular mission have patient number or acuity which exceeds the capabilities of the team, a critical care air transport extender team consisting of two additional critical care nurses may be added. A CCATT transporting three patients on mechanical ventilation, for example, would need an extender team to care for an additional critically ill or injured patient.

Transport equipment used by CCATT must be able to function without regard to changes in barometric pressure associated with changes in altitude, vibration, acceleration/deceleration, or temperature variations. Additionally, the equipment cannot interfere with or be affected by aircraft communication and navigation systems (20). All equipment employed by CCATTs is "off-the shelf" and was not designed specifically for aeromedical transport.

In the U.S. Air Force, equipment has to undergo rigorous testing by the Air Force Medical Equipment Development Laboratory (AFMEDL), Brooks City-Base, Texas. At the time of this writing, the primary monitor employed by CCATTs is the PROPAQ Encore 206 EL (Welch Allyn, Skaneateles Falls, NY). These monitors provide capability for continuous cardiac monitoring, noninvasive and invasive blood pressure monitoring, temperature monitoring, pulse oximetry, and continuous capnography. In addition to monitoring capabilities and a cardioversion/defibrillation function, the Zoll M-Series CCT (Zoll Medical Corporation, Chelsmford, MA) also provides CCATTs with the capability to perform 12-lead electrocardiograms, ST-segment analysis, and transcutaneous cardiac pacing.

When mechanical ventilation is required, CCATTs employ the Univent Eagle, Model 754 (Impact Instrumentation, West Caldwell, NJ) which is electronically controlled, time-cycled, and pressure limited. An internal compressor allows the FIO_2 to be adjusted from 0.21 to 1.0. The unit automatically adjusts the flow rate to compensate for changes in barometric pressure at 5,000 ft intervals up to 25,000 ft. However, this unit cannot provide some ventilator modalities such as pressure control and pressure support. This has posed challenges when attempting the transport of patients with severe ARDS. To overcome this limitation, the Pulmonetics LTV-1000 ventilator was conditionally approved for flight on U.S. Air Force aircraft in 2006 (23). This ventilator adds the pressure control and pressure support modalities lacking in the Univent Eagle, Model 754.

Infusion devices are the preferred means of delivering IV fluids and medications. CCATTs employ the IVAC Medsystem III (Cardinal Health, Dublin, OH), which provides three delivery channels for that purpose. Teams also employ point of care testing using the i-STAT blood analyzer (Abbott Medical Diagnostics Product, East Windsor, NJ). The CCATT equipment allowance standard also includes the portable IMPACT 326 Ultra-Lite suction device.

In the final analysis, the specific equipment choices may change. What is important is that they be sturdy enough to survive the rigors of deployment and certified by appropriate means to function "as advertised" in the aircraft environment. Additionally, it is critical that all team members are trained to use the equipment in that specific environment.

It is of interest to the AMP to understand the recent historical experiences of CCATTs. The U.S. Air Force has used CCATTs to augment AE crews deployed in support of various military operations including support of operation enduring freedom (OEF), under way in Afghanistan since October 2001 and Operation Iraqi Freedom (OIF) that has been ongoing since March 2003. CCATTs have also been deployed in support of a number of humanitarian operations including the national response to Hurricane Katrina in 2005. Between October 2001 and May 2006, CCATTs completed 3,478 patient movements of a total of 2,441 patients (some patients moved twice). These transports predominantly occurred between Iraq or Afghanistan and Landstuhl Regional Medical Center in Germany or between Germany and the continental United States. Of those patients, 76% had suffered multiple traumas and 64% were battle related. The combat casualties suffered their injuries from explosion in 59% of cases, fragmentation devices in 29%, and gunshot wounds in 17%. Types of injury included extremity fractures (73%), vascular injuries (35%), abdominal injuries (19%), chest trauma (17%), traumatic brain injury (TBI) (14%) and burns exceeding 15% total body surface area (13%).

Nonbattle injuries accounted for slightly more than 8% of patients transported by CCATTs. Another 25% suffered from a wide range of disease. These critically ill patients suffered from cardiac disease (55%), neurologic conditions (19%), vascular disease (11%), or infectious disease (11%) (24–26).

Of note, although 64% of CCATT patients had combat-related injuries, data from the DoD Joint Theater Trauma Registry indicates that just fewer than 32% of all casualties sustained a battle-related injury. This suggests the population of CCATT patients is more likely to be those with combat trauma. The study also found that 94% percent of CCATT patients with battle injury had at least one surgical procedure before transport. Additionally, 79% of all trauma patients and 13% of medical patients required mechanical ventilation. CCATTs regularly transported patients who had undergone a variety of surgical procedures including craniotomy, thoracotomy, laparotomy, ocular procedures, vascular repairs and a wide variety of orthopedic procedures including placement of external fixators, soft tissue debridements, and amputations. Many CCATT patients undergo invasive monitoring including 21% who required arterial pressure monitoring and 9% who required intracranial pressure monitoring (27).

While Air Force CCATTs perform most of the fixed-wing transports of critically ill and injured servicemen, the U.S. Army and U.S. Navy are also developing critical care transport capability for short duration, intratheater transports. Transport of casualties from near point of injury or forward care facilities to larger facilities in the theater of operations is usually performed using rotary wing aircraft. Maintaining ICU-level care during these transports can be problematic and the U.S. Army has addressed the challenge with the Joint *En Route* Care Course conducted at Ft Rucker, Alabama. There, trauma transport training is provided to U.S. Army flight medics, U.S. Navy critical care nurses, and other military medical personnel. In addition, the Army Institute for Surgical Research (ISR) Burn Team deploys transport teams that frequently work alongside CCATTs. These teams routinely transport burn casualties to the U.S. Army Burn Center in San Antonio, Texas within 2 to 3 days of injury.

Developing the capability to transport high-acuity, critically ill and injured patients have been accomplished with considerable success. Nevertheless, the experience has raised a number of questions that remain to be answered. The effect of aeromedical transports requiring 4, 8, or more hours to complete may have effects on medical outcomes that are not currently understood. The added effects of altitude and hypoxia on soft tissue edema may contribute to the development of tissue hypoxia and even compartment syndrome in the initial 24 to 48 hours after injury. There may also be effects on wound healing that have not been appreciated to date. The feasibility and risks of using negative pressure wound therapy during AE flights is also being studied. Further topics of study for the future include transfusion thresholds for casualties with acute hemorrhage before AE transport, use of closed loop control systems to optimize oxygen utilization during mechanical ventilation and improved lung protective strategies, and transportable patient warming/cooling systems. The transport of casualties with severe neurologic injuries also poses new questions. The effects of transient periods of acceleration on intensive care patients (ICP) and neurologic outcomes is poorly understood. In addition, there may be other transport-related causes of deterioration observed on occasion during transport of casualties with severe TBI.

SPECIFIC AEROMEDICAL ENVIRONMENTS

Aircraft Carrier–based Aviation Medicine

The unique environment of a U.S. Navy aircraft carrier presents exciting challenges for physicians assigned to provide health service to the embarked aviators and both aviation and nonaviation support personnel aboard. As the lead of a Carrier Strike Group (CSG), the carrier and its medical department share oversight of operations, both aviation and medical support, with other ships and squadrons in the group. The varying conditions of austerity and comfort, hazards and safety management, and occupational and daily living stress are always fluid in routine operations and can change dramatically when the Strike Group is called upon to answer urgent national security needs.

All functions of the CSG can be summarized in the mission "provide credible, sustained forward presence, conventional deterrence, and support aircraft attacks in sustained operations in war." Bluntly, the CSG exists to put bombs on target or turn jet fuel into destructive force whenever and wherever required—the "national security 911." In order to accomplish this, the human support required is substantial. Including only the aircraft carrier component, there are typically 5,600 people deployed to support 85 aircraft, approximately a 65:1 ratio. This is a complex system heavily reliant on people who are fit and stay healthy.

The mission of maintaining the fitness and health of the people falls primarily to the carrier medical department, headed by the Senior Medical Officer (SMO). The combination of general preventive medicine duties and providing both general medical and aviation medicine specific care has led to a tradition of placing a residency-trained aerospace medicine specialist physician in the SMO position on U.S. Navy aircraft carriers. One veteran of the job has likened it to being "the operator and chief of staff of a general community hospital, the chief public health officer for a community of 6,000 powered by a nuclear reactor, and the CEO of a small health maintenance organization (HMO)" all at the same time.

The austerity of the deployed carrier medical department in equipment and staffing descends from the medical consequences of the mission of the CSG. Restating the mission in terms of people, the CSG exists to create casualties, not sustain them. The number of people who could present to the medical departments for health care is known, all have been screened and deemed healthy, and historic records for injury and illness can be used to project requirements. Human casualties due to injury and illness above those historic benchmarks would very likely follow catastrophic damage, threatening the ship's survival and rendering medical support a secondary matter.

Typically, the staff supporting the medical department while conducting operations includes both medical officers (physicians, nurses, nurse practitioner or physician's assistant, ancillary health service providers) and dental officers organic to the ship (ship's company) and to the aircraft squadrons (air wing flight surgeons) and on temporary assignment (nurse anesthetist or anesthesiologist). Specifically, the specialty mix of providers includes the following:

Four to six physicians: aerospace medicine, general surgery, family medicine, two or three flight surgeons, possibly an anesthesiologist

Five ancillary/medical service corps officers: administration, physical therapy, radiation health, psychologist, nurse practitioner or physician's assistant

One critical care nurse, one certified registered nurse anesthetist (CRNA) (if anesthesiologist not temporarily assigned)

Five dentists (one oral maxillofacial surgeon)

The enlisted staff supporting the providers typically numbers approximately 50, with some qualified in specialized technical functions including laboratory, pharmacy, radiology, aviation medicine, surgery, preventive medicine, radiation health, optical fabrication, dental hygiene, and biomedical repair.

Two corpsmen with an enlisted rating unique to the Navy, the independent duty corpsman (IDC), are also assigned to the carrier. IDCs supervise the medical departments of five of the six other ships in the CSG. With nearly a physician's assistant level of responsibility, IDCs often transition to physician's assistants later in their careers. The other ships in the environment support group (ESG) have between 150 and 350 deployed personnel. Their medical departments are correspondingly smaller and less capable and use the carrier medical department as their "consult and referral" center. Although the other ships may have aviation personnel aboard, all aviation medicine matters must be deferred to the carrier medical department. The carrier's IDCs serve as backups to the other ships' medical support, particularly in the event that the other ship's IDC becomes ill or injured.

Space in the carrier medical department attempts to match the limited acute care role planned for the duration of a typical deployment of the CSG (6–8 months) with enough capability to sustain the community independently. Therefore, there is space in the medical department for 52 inpatients, three ICP, and one operating room. There is an aviation medicine space with a certified audiometry booth, a standard eye lane with equipment for refraction and slit lamp examination, and an optical fabrication area. Other specialized treatment or examination spaces may be devoted to pharmacy, x-ray, laboratory, physical therapy, general examinations, and psychological interviews.

Equipment is available for common laboratory studies such as chemistry, bacteriology, and hematology; for common, noncontrast plain radiography; for respirator support and monitoring of critical patients; for basic GI endoscopy, and limited diagnostic ultrasonography, for general endotracheal and spinal anesthesia; for major abdominal surgery and sterilizing of instruments; and for required health screenings. Medical supplies are planned around the typical needs of several thousand healthy young adults with an option for intermittent resupply in a matter of 1 or 2 weeks.

The Aircraft Carrier and Clinical Aviation Medicine

As outlined, the medical support of a CSG is a complex and multifaceted process. Planning, manning, and equipping of the medical department directly reflects the mission—bombs on target—which has aviation at its root. The special emphasis on aviation facets of the mission and medical support is reflected in the special capabilities enumerated. Routine aviation medicine duties (physical examination and qualification) take place in the space devoted to aviation medicine and provided by the airmen's own flight surgeon. Consultation among air wing flight surgeons and the SMO allows a reasoned approach to many challenging aviation medicine questions that surpass routine care.

Specific physical standards for aviation-related duty are not limited to pilots and aircrew. Aviation support personnel provide air traffic control, fuel, fix, and maintain aircraft on the ship, direct the intricate ballet of movement on the flight deck, launch and recover aircraft, and move, load, and maintain ordnance and aviation life-support systems. Navy regulations and policies have special physical standards for support personnel performing duties with particular requirements for vision, hearing, neurologic, and psychological functions. Physical qualification, initial and recurrent, of support personnel is another joint endeavor of the carrier's aviation medicine department that includes both air wing flight surgeons and aviation medicine technicians and the SMO and ship's aviation medicine technicians.

Aviation Medicine Consultation Support

Overall, the medical departments of a U.S. Navy aircraft carrier and the CSG are manned and equipped to provide a robust primary care level of health service support to the air wing and ship's crew. Everyone is screened and selected for physical and mental health with the expectation of routine acute illness and injury occurring over a defined length of deployment. A well-trained clinical primary care provider would find little difference in their practice from that of primary care in a typical small town.

The hazards inherent in a demanding aviation operations environment require significant additional expertise in occupational medicine and health hygiene. Together with an industrial hygienist assigned to the carrier safety department, the flight surgeons (air wing and SMO) on a deployed carrier are the subject matter experts their commands expect to supervise numerous occupational health and safety programs. These programs include hearing and sight conservation, heat stress, radiation health, immunizations, chronic infectious disease control (TB and HIV), drug and alcohol abuse prevention, traumatic injury hazard identification, and assessing and managing health risks of the crew going ashore in foreign countries.

Predicting and managing fatigue during around-the-clock operations and handling the psychological stresses of prolonged family separations and isolation of lengthy time at sea are other areas where aeromedical expertise becomes a welcome adjunct to primary care.

Finally, when the primary care capabilities of the carrier medical department and CSG are insufficient for a critically ill or injured crewman, the aeromedical physicians provide air evacuation expertise preparing patients for safe movement from the ship. The U.S. Navy and Marine Corps do not maintain aircraft dedicated to MEDEVAC. The particular combination of knowledge of clinical medicine, the aviation environment, the mission of the CSG, and the capabilities of available aircraft make the flight surgeon a vital resource in determining if, when, how, and where patients in the Strike Group are evacuated.

Education and Training of Aeromedical Specialists on Aircraft Carriers

Air Wing Flight Surgeons

The U.S. Navy has recognized the special requirements for providing primary care to aviation units since 1939 by establishing a course of instruction to achieve designation as a naval flight surgeon (NFS). Designation requires knowledge, skills, and attitudes acquired in the primary flight surgeon course conducted at the Naval Operational Medicine Institute (NOMI), Naval Aerospace Medical Institute detachment at Pensacola, Florida. The course of instruction includes an array of topics in clinical medicine, aviation physiology and medicine, environmental hazards, aircraft operations, safety, mishap investigation and administration (both medical administration and squadron operations). The content of the course of instruction has been established by the Chief of Naval Air Training (CNATRA) for required flight training and NOMI for required operational medicine.

By combining operational flight training and operational medicine training, designated NFSs are expected to integrate with their units. Rather than "going to the doctor," squadron aviators and support personnel see "their doc" for health care. Health services are usually provided in an established clinic at their home base. NFSs participate in operational monitoring of unit health both informally by spending time in other departments of the unit and formally in regular meetings that monitor individual performance and stress. NFSs are expected to actively participate in squadron safety programs with presentations on medical factors affecting flight.

There are typically two or three NFSs assigned to the air wing, and they accompany the air wing on carrier deployments. While maintaining their unit duties and integration, their clinical duties are performed in the carrier's medical department. Ideally, deployed air wing flight surgeons become fully integrated with the carrier medical department.

Senior Medical Officer

Paralleling the logic that assigns a designated Naval pilot or flight officer as Commanding Officer (CO) and Executive Officer (XO) of the aircraft carrier, the SMO on aircraft carriers is a designated NFS. Although they will have the education and training of a primary care NFS, the SMO has also established performance in the practice of aviation medicine. Ideally, the SMO has completed a residency in preventive medicine (aerospace). Training and education to a specialist level in preventive medicine prepares the SMO for the myriad of environment and occupational medicine duties that accompany his role as chief medical officer, supervising a small community size population that sustains its own water, sewage, power, and industry systems and processes. Alone amongst the department heads, the CO and XO rely on the SMO and the medical department to "maintain" the system common and irreplaceable to all the other departments—their people.

As a specialist in aerospace medicine, the residency-trained SMO can mentor the air wing flight surgeons in their practice of clinical aviation medicine. With heightened expertise in aeromedical qualifications matters and processes, the SMO can assist flight surgeons in resolving some issues that might otherwise require "grounding" awaiting policy decisions by distant authorities. In the event of an aircraft mishap, the SMO can step in to relieve the investigating flight surgeon from primary care in both aviation and nonaviation health support.

Research

As a large-scale approximation of a controlled laboratory environment, the aircraft carrier and air wing crew offers a unique environment for investigating an array of human factors and aviation, particularly in the arena of fatigue countermeasures, heat stress, injury patterns, prevention and noise, and other environmental exposures. The major limitations to original research are the usual—time and money—plus the clear subordination of all nonessential activities to the mission and sensitivity to finding and publishing "dirty laundry." Intervention studies would face additional legal hurdles without a consenting, Institutional Review Board, and clinical research authority established as expected in an academic or hospital setting.

Despite these obstacles, observations have been published identifying possible increased risk of sarcoidosis with carrier duty, hearing loss patterns, and effective case management of a TB outbreak. Novel approaches to monitoring hearing loss and increasing heat stress tolerance have been investigated during carrier deployments with analysis and results restricted to Navy policy and procurement authorities.

THE TERRAIN HIGH-ALTITUDE ENVIRONMENT

AMPs are experts on the effects of altitude in the flying environment. Conditions including trapped gas, acute hypoxia, and decompression illness are well understood. However, operational demands may require the military or civilian AMP to support personnel during missions where they are operating for extended periods of time at high-terrain elevations. These environments require the AMP to use his/her skill and knowledge both in the planning and execution of the mission to insure the health and safety of the personnel and to insure mission success. The high-terrain altitude environment can be one of the most difficult environments to work in. It universally places significant stress on the personnel. Furthermore, their individual reactions to those stresses are impossible to predict. The AMP planning to support missions in this environment will need to understand the many manifestations of altitude illness as well as the strength and endurance limitations that high altitude presents.

The terrain high-altitude environment poses a very different threat to the individual exposed than does the high-altitude, flying environment. As in the flying environment, it is the decreased barometric pressure and associated decrease in ambient oxygen tension that provides the stress. However, although the terrain high-altitude environment is typically less extreme in terms of the altitudes experienced, it must be tolerated for days or weeks rather than hours. This drives a completely different set of physiologic responses and challenges to which the AMP must anticipate and respond. This chapter is not meant to be an in-depth discussion of altitude and associated illness. The AMP desiring more information about these conditions is referred to one of several references in the **Recommended Readings** at the end of the chapter.

For simplification, terrain altitudes can be divided into three different ranges. High altitude falls between 5,000 and 11,000 ft, very high altitude between 11,000 and 18,000 ft, and extreme altitude above 18,000 ft. Barometric pressure drops in a logarithmic manner as altitude increases as defined by the equation $P_B = 760(e^{-alt/7924})$ where alt = altitude above sea level in meters. The normal, 760 mm Hg barometric pressure at sea level drops to 627 mm Hg by 5,000 ft and 500 mm Hg by 11,000 ft. At 18,000 ft it is 380 mm Hg—half what it was a sea level. At the top of Mount Everest over 29,000 ft, it is 250 mm Hg. The relative concentration of oxygen at 21% remains essentially constant throughout this range.

At high altitude, between 5,000 and 11,000 ft, personnel can expect decreased exercise performance and a noticeable increase in minute ventilation. The relative Sa_{O_2} in healthy personnel remains more than 90%. Symptoms of altitude illness typically occur above 8,000 ft, but can occur at lower altitudes. Symptoms, which are usually mild, will be experienced by approximately 25% of personnel with rapid ascent. At very high altitude, between 11,000 and 18,000, the Sa_{O_2} drops below 90% and symptoms of altitude illness will be present in 85% of personnel who rapidly ascend to these altitudes. While mild symptoms still dominate, severe altitude illness is relatively more common. However, for most healthy people, acclimatization is still possible. Extreme high altitude is above 18,000 ft. These altitudes are characterized by marked hypoxemia and hypocapnea. Rapid ascent to these altitudes is very dangerous. However, in most situations the severity of the hypoxia limits the ability to stay and work at these altitudes long enough to develop altitude illness. Acclimatization to these extreme altitudes is not possible and people do not live in these ranges.

The fact that people around the world live and work at high and in some cases very high altitude testify to the successful physiologic adaptations that can be achieved. The ability to make these adaptations allows personnel making the change to higher altitudes to acclimate. These adaptations include physiologic strategies to increase the delivery of oxygen to tissues. Specific adaptations include an increase in minute ventilation, increased cardiac output, increased cerebral blood flow, increased red blood cell mass, increased capillary density, and increased mitochondria. The failure to successfully make these adaptations can result in symptoms of altitude illness. In addition, these adaptations require time to complete so even those who are ultimately able to successfully acclimate may experience symptoms as they make necessary adaptations. Furthermore, some adaptations may actually cause illness. For example, one response to decreased oxygen tension is increased pulmonary artery pressure. This response can protect the individual who aspirates and occludes a discreet portion of a lung by directing blood flow away from the occluded segment. However, in the high-altitude environment with global relative hypoxia, it is not a functional adaptation and can result in significant illness. The AMP planning to support aviators and other personnel in these environments should have a basic understanding of altitude illness and how it may be prevented, identified, and treated.

Manifestations of altitude illness can range from mild discomfort to death from central nervous system (CNS) or pulmonary pathology. The most frequent symptoms include disturbed sleep patterns with frequent arousals and shortened overall sleep time (28). This is caused by respiratory changes that mimic the symptoms of sleep apnea. In the case of altitude, the individual has increased his/her minute ventilation rate in response to the decreased P_{IO_2}. This hyperventilation results in a respiratory alkalosis that then results in a period of apnea. The apneic period both drops P_{O_2} and raises P_{CO_2} at which point respiration is stimulated and the cycle begins again. Just as in sleep apnea, the transitions are disruptive to sleep quality and patients experience it as frequent arousals with decreased sleep quality. In general this phenomenon will be experienced by approximately one fourth of people who ascend to 8,000 ft and by essentially everyone by 12,000 ft. Another symptom of altitude exposure that is essentially universal is decreased exercise tolerance. Personnel from sea level experience a 10%

drop in VO_2 maximum at 5,000 ft and an additional 10% with every 3,000 ft above that (29). Interestingly, submaximal endurance can be increased by acclimatization but maximal aerobic output cannot be increased. Time for full exercise acclimatization takes 10 to 20 days at 6,000 ft, longer as altitudes increase.

The constellation of relatively mild symptoms that is the most common altitude illness is called *acute mountain sickness* (AMS). The symptoms of AMS are relatively nonspecific and are jokingly referred to as a hangover without the memories. Prominent features include a throbbing, bitemporal headache, and dizziness without ataxia. Anorexia and a dry cough are common features. Patients will describe fatigue with dyspnea on exertion but this is very nonspecific as everyone experiences this at altitude. Up to 25% of these patients will have rales on pulmonary auscultation. Dyspnea at rest suggests development of the more serious high-altitude pulmonary edema (HAPE). The differential diagnosis in these cases includes simple upper respiratory infection, exhaustion, dehydration, hypothermia, and CO poisoning. Of those who develop AMS, 60% resolve in 12 to 72 hours without specific therapy, 30% take longer but ultimately resolve in 7 to 21 days, 2% never acclimate but do not progress and 8% go on to develop the more severe conditions of high-altitude cerebral edema (HACE) or HAPE.

Treatment options for AMS are limited. The first step is to halt the ascent and wait at the altitude where symptoms first developed. For many personnel who are arriving at a high-terrain altitude by aircraft, this may not really apply. However, they should clearly not continue to any higher altitude. If there is no improvement in 24 hours the next step should be to descend 1,500 to 3,000 ft for a night and look for improvement. A reasonable adjunct therapy is Acetazolamide 125–250 mg b.i.d. This diuretic causes a mild, metabolic acidosis that drives an increased minute ventilation and tends to prevent or lessen the symptoms of altitude (30). It may be helpful to objectify the status of patients suffering from AMS to decide if they are worsening or improving. The Lake Louise AMS scoring system (31) is a good tool for objectively tracking symptoms and severity of altitude illness, and should be considered for use in nonacclimatized high-altitude inhabitants.

AMS can progress to the more serious conditions of HACE and HAPE, both of which are life threatening and should be treated as medical emergencies. HACE is characterized clinically by a progression to encephalopathy in the setting of AMS or HAPE. The symptoms of HACE are presumably related to brain swelling. This is felt to be due to increased cerebral blood flow driven by a requirement to maintain sufficient oxygen delivery to the brain tissues. However, as the increased flow increases pressure, a vasogenic edema begins and progresses to the point that transport of nutrients and oxygen from the capillaries to the tissues becomes compromised. This in turn leads to ischemic cells and intracellular edema that further raises intracranial pressure. Lumbar punctures in cases of HACE have revealed markedly elevated cerebrospinal fluid (CSF) pressures of more than 300 mm Hg (32). This may result in a myriad of neurologic symptoms but is classically seen as alteration in consciousness and ataxia without focal neurologic signs. The exact distinction between HACE and AMS is indistinct as HACE can be thought of as a progression to a more extreme form of cerebral AMS.

Treatment of HACE requires early recognition and attempts to return to a more normal physiological state. At the first signs of ataxia or change in consciousness, descent should be initiated. The AMP must be prepared for this as descent may be difficult and require assistance from several additional personnel. Dexamethasone 4–8 mg IV or IM followed by 4 mg every 6 hours should be administered with O_2 to 4 L/min by mask if available. If pulse oximetry is available, O_2 may be titrated to 90% SaO_2. If intubated, excessive hyperventilation should be avoided. Although commonly used at sea level to lower intracranial pressure, these patients are already relatively alkalotic and further hyperventilation could result in cerebral ischemia. Similarly, treatment with loop diuretics can reduce brain swelling but must be carefully balanced against the chance of reducing perfusion pressure and further increasing brain ischemia. Treatment with steroids and oxygen is understandably successful if initiated early in the course but often disappointing if delayed until unconsciousness or coma ensues. The AMP must be alert to the potential for HACE especially during the first days after personnel arrive at high-terrain altitudes. Perhaps more importantly, they must insure the mission personnel are aware of the symptoms and are primed to refer suspicious cases for evaluation to avoid unnecessary late presentations.

The other potential progression of AMS is development of HAPE. Following ascent, HAPE symptoms include dyspnea at rest, cough, weakness, or decreased exercise performance, accompanied by pulmonary crackles or wheezing, tachypnea, tachycardia, or central cyanosis. HAPE is the most common cause of death related to high altitude and is a major threat to personnel who ascent quickly to very high altitude. Development of HAPE is classically delayed after ascent to altitude usually occurring on days 2 to 4, often on the second night. Not all cases are typical, however, and it can develop abruptly, particularly in sedentary individuals who do not notice the early stages (33). The symptoms of HAPE typically develop in the setting of AMS. The development of dyspnea at rest heralds the transition from AMS to HAPE. Severe hypoxemia may produce mental status changes, ataxia, or coma all of which raise the question of HACE.

The most likely explanation for the development of HAPE is overperfusion edema. In this model, increased pulmonary artery pressures result from activation of the hypoxic pulmonary vasoconstrictor response at altitude. The global hypoxia at altitude results in constricted pulmonary vascular bed with resultant increased pulmonary artery pressure. The degree and distribution of this vascular constriction will vary between individuals. In some individuals, areas of relatively less constricted vasculature will be subjected to increased pressure and flow. This may result in endothelial damage and stress failure of capillary membranes which, in turn, allows a high-protein permeability leak. This may explain why those who are very fit are sometimes more likely to develop HAPE as they push themselves at altitude driving up cardiac output and pushing more blood through the susceptible pulmonary vasculature. It is important to note that although there is good evidence to support this theory, testing of this hypothesis in humans is understandably limited.

As with HACE, treatment is far more successful if initiated early in the chain of events than later. Increasing oxygenation is crucial and can be accomplished temporarily with administration of O_2. This treatment will often be required for 24 hours or more so arrangements for descent should be initiated immediately. Patients may respond remarkably well to small elevation changes, often as little as 1,000 ft. Treatment with a hyperbaric (Gamow) bag can be lifesaving. Medications that reduce pulmonary vascular resistance can be helpful. Perhaps the one least likely to have untoward side effects is Nifedipine. Recovery after descent is typically rapid and complete though a short period of hospitalization and oxygenation to maintain SaO_2 above 90% may be warranted.

When possible, a graded ascent to altitude prevents most severe altitude illness. Two to three nights spent at 7,500 to 9,000 ft followed by one night for every increase of 1,000 to 1,500 ft. For every 3,000 ft altitude gain, personnel should spend a second night at the same elevation before continuing. Unfortunately, personnel who are transported to sites for missions that would be supported by the AMP often arrive at by air without any time for acclimatization. Flights can easily carry passengers from sea level locations to international airport locations as high as 12,000 ft without the benefit of gradual acclimatization. Nonacclimatized personnel should try to avoid physical work (including exercise) for the first two days at altitude, and gradually increase to full duty over the next 3 days (34). Alcohol and sedative medications should be avoided. Prophylactic use of Acetazolamide and Nifedipine can reduce development of AMS, HACE, and HAPE. Research efforts to look at the use of NO_2 medication such as Viagra for high-altitude exposure to reduce vascular resistance are showing promise as well.

In developing the medical threat assessment and mitigation plan, the AMP must recognize that going to high-terrain altitude is a significant stress. The usual threat of altitude, exacerbated by the limited opportunity to acclimate, should alert the AMP to a higher-than-usual likelihood of altitude illness that may be experienced by their supported personnel. They must function in their consultant role to the leadership to explain that the mission personnel will have reduced work capacity. Additionally, a portion of their number will likely suffer altitude illness that will require at least descent and rest if not complete redeployment home. Mission planning must include sufficient personnel to cover these limitations and losses if the mission is to succeed. In addition, personnel selected to deploy to the high-altitude mission should be screened for conditions that will likely worsen outcomes at altitude. For example, anemia detected at sea level has a more profound effect at altitude due to decreased oxygen tension. Similarly, the hypoxia of untreated sleep apnea is worsened with altitude exposure. The periodic breathing associated with altitude combined with that from sleep apnea lowers oxygen saturation even more, placing these individuals at increased risk for altitude illness.

Obesity and low fitness levels may not directly correlate with susceptibility to altitude illness; however, those personnel may have less exercise tolerance and greater fatigue at altitude. Asthma may actually improve at altitude because of the concomitant increase in serum cortisol and norepinephrine (34), but episodes may be induced with cold exposure or the exercise related to ascent on foot. Age-appropriate screening examinations (colonoscopy, Pap smear, mammogram, dental) need to be accomplished before departure for assignments in remote environments as evacuation may be difficult or impossible. Women of childbearing age should obtain a pregnancy test. Effective screening helps reduce risk to personnel and helps avoid evacuation requirements.

This is especially true in remote, high-altitude environments where descent may not always be possible. Evacuation by aircraft will be dependent on both availability and weather. Evacuation/descent by land is not always feasible due to weather or mission requirements. It may be necessary to hold an individual with altitude illness for several hours or days, awaiting transportation. Various treatment protocols for HAPE and HACE are available. Hackett's High-Altitude Medicine chapter in Wilderness Medicine and ***UpToDate*** (**Suggested Readings**) are good, concise references for altitude physiology, diagnosis, and treatment of altitude illness.

Several portable hyperbaric devices are commercially available. These systems give patients up to 2 psi of pressure, effecting a physiologic descent. The magnitude of descent depends on the altitude where the device is actually used. The Gamow bag, Certec bag, and Portable Altitude Chamber are all relatively lightweight and portable. The Hyperlite is heavier, but a good choice for larger base camps and nonrescue situations. Patients who are comatose, unable to maintain their airway, or who require ventilation cannot be safely treated in any of these devices. Gamow makes a hyperbaric tent system, which can accommodate two patients, or one plus an attendant. Portable bags can be labor-intensive to use because they require continuous pumping to prevent CO_2 buildup inside the bag. Nevertheless, they can mean the difference between life and death in some cases.

It may be necessary for mission-essential workers who developed altitude illness to return to the location after treatment and recovery at lower altitude. Workers recovering from HAPE or HACE are at increased risk of recurrence on return to altitude. The degree of this risk is unclear as there is a paucity of literature regarding the return of workers after HAPE. At a minimum, they should have a normal cardiopulmonary examination with a clear chest x-ray, resting oxygen saturation above 96% at rest, and above 92% on exertion. These workers should receive prophylactic medications and follow strict rest-work restrictions. Post–HAPE cough may last for weeks to months, complicating the diagnosis of recurrence when they return to altitude.

Environmental factors must always be accounted for when responding to mishaps in high altitude and polar environments. Shelter, water, and food become even more critical than normal. Work-rest cycles, work high-sleep low arrangements, and prophylactic medications should be considered. The availability of a pressure chamber or portable hyperbaric system, oxygen, and a well-prepared evacuation plan are essential.

Altitude research is ongoing, multinational, and multiagency. Much of this research focuses on performance enhancement tailored to the environment or task, prevention of altitude illness, and treatment of altitude illness. Studies for physiological, chemical, and genetic biomarkers of altitude illness susceptibility are being conducted worldwide, at altitude and in altitude chambers. Some potential markers include heart rate variability, muscle fatigability, and indicators of physiological stress such as malondialdehyde and lipid peroxide levels. Some of these biomarkers show promise; however, their utility remains experimental.

In conclusion, there are more treatment options available to the AMP than when Sir Edmund Hillary summitted Mount Everest in 1953. However, descent and supplemental oxygen remain the most effective treatment for altitude illness and there are still no reliable tests to predict susceptibility to it. With the lay public increasingly interested in adventure travel, and the placement of telescopes and other facilities at high altitude, the ability to predict which personnel would be susceptible to altitude has financial, operational, and occupational significance. Research in this area continues to be extensive.

THE POLAR ENVIRONMENT

Antarctica is a land of superlatives. It is the coldest, windiest, driest, highest, and most austere continent on Earth. With limited air and sea access and no physical infrastructure, it is also the most remote. Despite being nearly covered by an ice sheet, it receives only approximately 2 in. of precipitation per year (35). Conditions vary widely between the perpetually dark austral winter and the constant daylight of the austral summer. Temperatures vary from −128°F (−89°C) to 59°F (15°C). The atmosphere is thinner and barometric pressure at polar altitude is typically 20% lower than expected for the same altitude at mid-latitude. Lower barometric pressure translates to lower partial pressures of oxygen and a higher physiologic altitude (36). Regardless of latitude, weather patterns at altitudes greater than 6,000 ft can be variable and volatile.

Extremes of weather, temperature, and altitude result in exacerbated or atypical physiologic responses to environmental exposures. Shelter becomes imperative, and survival time outdoors is minimal without proper shelter or extreme cold weather (ECW) clothing. Still, humans continue to visit and inhabit these inhospitable areas. Tourism, scientific experimentation, exploration, and military operations are just a few of the scenarios an AMP may be tasked to support.

Clinical Aviation Medicine in the Polar Environment

Unlike the relatively more hospitable Arctic, there is no indigenous population in the Antarctic. However, many scientists and support personnel as well as occasional tourists travel to the region. AMPs are employed to provide care to the aircrew members who support the stations in the region. The largest station is McMurdo, which is located on the Ross Ice Shelf and has a population of approximately 1,500 personnel in the summer and 200 in the winter.

In general, polar medical problems are similar to nonpolar ones. Minor injuries, viral respiratory and gastrointestinal illnesses, dermatologic, and musculoskeletal problems occur regularly. The difference is that all of these occur in an occupational setting in the Antarctic. This unique environment affects both the presentation and the physiologic response to injury and illness. In addition, the Antarctic environment presents a near constant threat of severe cold injury should the individual make a mistake that leads him or her to be away from the support base at the wrong time or for too long. The AMP must consider these injuries in both the patients she/he expects to see and the threats she/he will face personally.

Cold injuries are not unique to the Antarctic. However, there is no colder environment and therefore the opportunity for cold injuries to occur is extremely high and frostbite and hypothermia are constant threats. At −70°F exposed skin can freeze and an individual can suffer frostbite in a matter of minutes. For personnel working with liquids such as fuel or hydraulic fluid a small spill can cause near instantaneous injury. Even appropriate personal protective gear is very limited. At −100°F an inactive person in full polar clothing could experience life-threatening hypothermia in 20 minutes. For a more complete discussion of cold injuries, we refer you to the textbook of Wilderness Medicine, Management of Wilderness, and Environmental Emergencies.

Aerospace and Occupational Medicine Issues

With the exception of the rare tourist, everyone on Antarctica is a worker. This may increase the risk as personnel attempt to do work in this environment. Workers may choose to remove pieces of the ECW gear because it is bulky or uncomfortable (full ECW gear can weigh 25 lb). This is especially true for tasks involving manual dexterity; workers frequently remove their gloves, exposing their fingers and hands to the cold. Risk of cold injuries is increased, and injuries sustained may not be noticed immediately due to decreased sensation.

Because air travel is only safely accomplished during the short Antarctic summer, every air mission is essential to accomplish the scientific mission. Twenty-four–hour operations and 12-hour crew days are standard. Aircrew, understanding the impact of canceling flights, may be reluctant to seek medical treatment. Just as in any demanding mission scenario, it is important for the flight surgeon to have a good rapport with the crews such that they are comfortable seeking advice and care early when needed.

Personnel planning to work in the polar environment should undergo thorough medical screening. Some conditions worsen with exposure to cold or altitude. Diabetic patients find it difficult to control blood sugar, which can vary widely under physiologic stress. Hypertension can worsen in response to cold weather. Personnel with a history of cardiac arrhythmias may find increased frequency of arrhythmias. Furthermore, as the ability to provide complex or difficult care will be limited, anyone likely to require such care should be excluded.

The role of the aeromedical consultant spans aerospace, preventive, occupational, and operational medicine. Pressure to complete the mission (during the short Antarctic summer, for example) is constantly balanced against the needs and safety of the people performing the mission. The aerospace medicine professional would be expected to provide the mission commander with scheduling and fatigue management guidance as well as knowledge about the relevant issues affecting the flying unit. Common issues include visual illusions and spatial disorientation (given the white-on-white sky vs. ground), sleep hygiene problems in the crowded, 24/7 environment, and protection from the intensely cold environment.

In the preventive medicine role, the aerospace medicine physician may be responsible for insuring food safety. This often includes management of numerous small camps or research sites in the area, each with its own cooking facilities. Specialized food preparation staff may not be available at some of these locations and the AMP may need to ensure small teams leaving the main camp for these locations are educated on safe food preparation and storage. Of note, food planning should recognize the need for the 25% to 50% greater caloric requirements for work in extreme cold (29).

Communicable diseases spread quickly when personnel work and sleep in crowded quarters, small tents, or buildings without adequate ventilation. In cold weather, individuals may be inclined to neglect good sanitation practices. Personnel on location should be periodically educated on hand washing, cough etiquette, and basic personal hygiene. Ensuring hand-washing facilities are available and utilized at the entrance to the dining facility can go a long way to preventing GI disease.

Adequate quantities of potable water must be provided. Many people are less inclined to drink water in cold environments. Although they may not be perspiring, much moisture is lost in exhaled air. Dehydration is still a risk in the cold and at altitude. Surface snow and ice should not be considered safe to drink without proper purification. Once established, potable water sources should be monitored for bacterial content.

Although employees should be thoroughly screened before arrival at remote polar locations there may be short-notice screenings requiring the opinion and disposition of the AMP. You may also need to determine fitness for duty after recuperation from an injury or illness. The aeromedical specialist, given their understanding of altitude physiology, may be consulted on operational hyperbarics. Scuba divers work beneath the polar ice conducting research and construction projects. Despite duplicate systems, regulators may freeze or free-flow in cold water. Divers may panic and surface rapidly, resulting in decompression sickness. Hypothermia, nitrogen narcosis, and disorientation add to the risk of polar diving operations.

AMPs will also be consulted for their expertise in emergency response and mishap investigation. Rapid weather changes, visual illusions, and other environmental issues make flying much more challenging in the polar regions. The last military Antarctic aviation accident was an LC-130 in 1987, killing two U.S. military personnel. There have been other mishaps in the Arctic and many at altitudes greater than 10,000 ft. When practicable, aircrews should never be comprised of entirely area-naive crews. A combination of new and experienced crewmembers enhances CRM. Environmental factors must always be accounted for when responding to mishaps in the polar environments. Shelter, water, and food become even more critical than normal.

Despite adequate screening and good preventive and occupational medicine, medical emergencies in the form of severe illness and trauma occur. The AMP will be asked to consult on evacuation issues, including timing and prioritization. At long-established bases in Antarctica, helicopters and trained SAR teams are always on call. Evacuation is nearly impossible during polar winters, and weather delays are common even in the polar summer. Local treatment options are limited and patients must be evacuated to the appropriate level of definitive care. For every patient evacuated, mission-essential cargo or personnel are displaced. These critical decisions cannot be made lightly and require the AMP to be familiar with both the medical issues of the patient as well as the overall mission requirements if they are to make balanced and appropriate recommendations for leadership.

In addition to evacuation decisions, the aeromedical physician may be asked to train SAR teams. Polar rescue teams require specialized training including ice and high-angle rescue and treatment of hypothermia. Teams should conduct realistic training exercises monthly, with scenarios appropriate for the terrain and climate. The AMP should insure that medical issues of rescue are properly considered and that the entire operation is integrated to insure the best possible outcome.

Specific occupational exposures include chemical dermatitis for ice drill operators, cooks and mechanics with overuse injuries, scientists bitten by seals and trauma from falls and vehicle accidents. Fire is considered "the major concern and principal danger at all Antarctic stations" (37). Safety and injury prevention must be emphasized on all levels.

OTHER CHALLENGES OF THE POLAR ENVIRONMENT

The polar climate varies from complete darkness in winter to constant daylight in summer. Both of these conditions have psychological effects on the population. Constant darkness can affect melatonin and thyroxine levels, resulting in seasonal affective disorder (SAD), depression, irritability, and hypersomnia. In contrast, the 24 hours of daylight can result in fatigue from insomnia. Treatment of light-induced insomnia includes room darkening and occasional use of sleep-inducing medications.

The effect of cold environments on thyroid hormone production has been studied for several decades. Cold-induced deficits of T3 and T4 may contribute to the fatigue, irritability, and depression suffered by approximately 50% of Antarctic residents who over-winter on the ice. New studies are investigating the value of prophylactic supplementation with thyroxine and tyrosine to improve alertness, memory, mood, and fatigue (38) in this population. Changes in melatonin levels in polar environments have given rise to continued research for SAD treatment and prevention. These studies include the use of 10,000 lux full-spectrum lights at least 30 minutes a day (39). Other research algorithms have looked at diet, exercise, antidepressants, and melatonin supplementation for treatment of SAD.

In addition to SAD, the sense of isolation in polar and high-altitude regions can be overwhelming. Small group dynamics and stress can be magnified in this austere environment. Family and relationship problems are especially distressing as many personnel are "required" and it may be very difficult to return from Antarctica early even in cases of significant family distress at home.

Despite these challenges, most personnel function well in the environment. Many develop a sense of pride in how many seasons they have worked, how many days they have spent on the ice, and the number of seasons they have "wintered over." This attitude is similar to the camaraderie found among some military deployments and is a key psychological adaptation. However, just as with military deployments, personnel may require up to 6 months to "normalize" to family and society on return from the ice. The AMP assigned to support personnel in this environment must remember to ensure workers returning from long-term remote assignments are equipped with resources to cope with this additional stress.

REFERENCES

1. The Air Medical Physician Association. 383 F Street, Salt Lake City, UT 84103. (801) 408–3699, www.ampa.org.
2. The Aerospace Medical Association. 320 S. Henry Street, Alexandria, VA 22314–3579. (703) 739–2240. www.asma.org.
3. Macnab AJ. Air medical transport: "hot air" and a French lesson. *J Air Med Transp* 1992;11:15.
4. Moylan JA. Impact of helicopters on trauma care and clinical results. *Ann Surg* 1988;208:673–678.
5. Meier DR, Samper ER. Evolution of civil aeromedical helicopter aviation. *South Med J* 1989;82:885–891.
6. Reddick EJ. Evaluation of the helicopter in aeromedical transfers. *Aviat Space Environ Med* 1979;50:168–170.
7. Neel SH. Army aeromedical evacuation procedures in Vietnam: implications for rural America. *JAMA* 1968;204:309–313.
8. Vido DA. *The impact of rotorcraft aeromedical emergency care services on trauma mortality: a critical analysis of the literature*. [Master of Science Thesis]. Baltimore: University of Maryland, 1986.
9. Rau W. 1999 Annual transport statistics and fees survey. *Air Med J* 1999;5:20–23.
10. Commission on Accreditation of Medical Transport Systems. PO Box 1305, Anderson, SC 29622. (864) 287–4177, www.camts.org.
11. Rau W. 2000 Helicopter avionics and operations survey. *Air Med J* 2000;6:25–29.
12. Air Transport Medicine Committee, Aerospace Medical Association. *Medical guidelines for airline travel*. Vol. 703. Alexandria: Aerospace Medical Association, 1997:739–2240;http://www.asma.org/.
13. Bruhn J, Williams K, Aghababian R. True costs of air medical *vs*. ground ambulance systems. *Air Med J* 1993;12:262–268.
14. Dodd RS. *Factors related to occupant crash survival in emergency medical service helicopters*. [Doctor of Science Dissertation]. Baltimore: School of Hygiene and Public Health, Johns Hopkins University, 1992.
15. Williams K, Rose W, Simon R. Teamwork in emergency medical services. *Air Med J* 1999;18:4.
16. Williams K, Aghababian R, Shaughnessy M. Statewide EMS helicopter utilization review: the Massachusetts experience. *J Air Med Transp* 1990;9:14–18.
17. *Fed Regist* 2000;65(177):55077–55100. Tuesday, September 12, [00–23195].
18. Eastman D, McClaine K, et al. Unpublished data presented at Rhode Island-American College of Emergency Physicians Summer Symposium, August 1999.
19. Holcomb JB. The 2004 fitts lecture: current perspectives on combat casualty care. *J Trauma* 2005;59:990–1002.
20. Grissom TE, Farmer JC. The provision of sophisticated critical care beyond the Hospital: lessons learned from physiology and military experiences that apply to civil disaster medical response. *Crit Care Med* 2005;33(1 Suppl):S13–S21.
21. Gawande A. Casualties of war-military care for the wounded from iraq and afghanistan. *N Engl J Med* 2004;35124:2471–2475.
22. Critical Care Air Transport Teams. *Air force tactics, techniques, and procedures (AFTTP)*. 2006. 3–42.51.
23. *Air force medical equipment development laboratory status guide*. At https://afml.ft-detrick.af.mil/AFMLO/AFMEDL/, 2007.
24. Data provided by Global Patient Movement Request Center. *USAF Air Mobility Command*, as of 5 Jan 2007.
25. Bridges E, Evers K, Taylor L, et al. Wartime critical care air transport (Oct 2001-May 2006). [abstract]. Presented at *The Amsus 112th Annual Meeting*, 2006. (submitted for publication.)
26. Mason PE, Eadie JS, Holder AD. United States air force critical care air transport teams in operation iraqi freedom: a prospective study [abstract]. *Ann Emerg Med* 2006;48(4):S104.
27. Bridges E, Woods S, Evers K. Invasive pressure monitoring at altitude [abstract]. *Crit Care Med* 2005;33(Suppl):12.
28. Reite M, Jackson D, Cahoon RL, et al. Sleep physiology at high altitude. *Electroencephalogr Clin Neurophysiol* 1975;38:463.
29. Buskirk ER, Kollias J, Akers RF, et al. Maximal performance at altitude and return from altitude in conditioned runners. *J Appl Physiol* 1967;23(2):259.
30. Office of the Surgeon General, Department of the Army. Medical aspects of harsh environments. *The textbook of military medicine*. Vols. 1 and 2. Washington, DC: Office of the Surgeon General, Department of the Army, 2001.
31. Sutton JR. The lake Louise consensus on the definition and quantification of altitude illness. In: Coates G, Houston CS, eds.

Hypoxia and mountain medicine. Burlington, Vermont: Queen City Printers, 1992. Clinical scoring tool available at: http://www.high-altitude-medicine.com/AMS-worksheet.html.
32. Houston CS, Dickinson JG. Cerebral form of high altitude illness. *Lancet* 1975;2(7938):758.
33. Viswanathan R, Subramianian S, Radha TG. Effect of hypoxia on regional lung perfusion, by scanning. *Respiration* 1979;37:142.
34. Hultgren H. *High altitude medicine*. Stanford: Hultgren Publications, 1997:174.
35. US Antarctic Program website, http://www.usap.gov/, 2007.
36. *US Antarctic welcome packet literature and hand-outs*. Additional information available at the USAP website, http://www.usap.gov, 2007.
37. Fowler A. Antarctic logistics. *Oceanus* 1988;31(2):80.
38. Reed HL, Reedy KR, Palinkas LA, et al. Impairment in cognitive and exercise performance during prolonged Antarctic residence: effect of thyroxine supplementation in the polar triiodothyronine syndrome. *J Clin Endocrinol Metab* 2001;86(1):110–116.
39. Kasper S, Rogers SL. Phototherapy in individuals with and without subsyndromal seasonal affective disorder. *Arch Gen Psychiatry* 1989;46(9):837–844.

RECOMMENDED READINGS

Aerospace Medical Association. *Medical guidelines for airline travel.* Alexandria: Aerospace Medical Association, 1997.
Auerbach P. *Wilderness Medicine*, 4th ed. Mosby, 2001.
Blumen I, ed. *Principles and direction of air medical transport.* Salt Lake City: Air Medical Physician Association, 2006. http://www.ampa.org/.
Saunders CE. Aeromedical transport. In: Auerbach PS, Geehr EC, eds. *Management of wilderness and environmental emergencies*, 2nd ed. St. Louis: CV Mosby, 1989.
Williams K. Air medical systems. In: Harwood-Nuss, L, eds. *Emergency medicine*, 3rd ed. Philadelphia: Lippincott, Williams & Wilkins, 2000.
UpToDate®, available at http://www.utdol.com/utd/store/index.do

CHAPTER 27

Aerospace Medicine Issues in Unique Aircraft Types

Richard S. Williams, Stephen L. Carpenter, Denise L. Baisden, Arnold A. Angelici, Jr., Stephen A. Bernstein, John A. Smyrski III, Dougal B. Watson, Shean E. Phelps, Kevin W. Williams, and Melchor J. Antuñano

The greatest danger for most of us is not that our aim is too high and we miss it, but that it is too low and we reach it.

—*Michelangelo*

AEROBATICS

Unique Aspects of Aerobatics Flight

Aerobatic flight, like many advances in aviation, had its inception in warfare. Aircraft in World War I were initially employed in an observation role, but rapidly progressed to become powerful offensive weapons platforms. Pilots began shooting at each other, first with small arms and then with automatic weapons mounted on the aircraft. The ability to maneuver abruptly and swiftly to evade the enemy or gain a position of advantage became an absolute necessity, giving rise to the principles of aerial combat and, as an essential requirement for effective aerial maneuvering, aerobatic flight.

Aerobatic flight, according to the Federal Aviation Regulations, Section 91.303, is defined as an intentional maneuver involving an abrupt change in an aircraft's attitude, an abnormal attitude, or abnormal acceleration, not necessary for normal flight. Aerobatic flight has long been recognized to have inherent risks, which, if not managed appropriately, can lead to catastrophic consequences for pilot, aircraft, and personnel on the ground. Some of these risks include failure of the airframe due to excessive acceleration forces, loss of situational awareness and increased chance of collision with other aircraft or the ground, and physiological compromise with loss of ability to control the aircraft. For these reasons, the Federal Aviation Administration (FAA) has placed restrictions against conducting aerobatic flight over congested areas, over an open-air assembly of persons, within airspace designated for an airport, within 4 nautical miles of the center of a federal airway, below an altitude of 1,500 ft above the surface, or when visibility is less than 3 statute miles. Aerobatic flight has great potential to reduce risk as well. Pilots who are trained in aerobatic flight are generally comfortable in most flight attitudes, including highly unusual ones. They more fully explore the entire flight envelope of aircraft, not just climbing, descending, and turning. They develop a better feel and sensitivity for aircraft. Aerobatic flying skills can be used to great effect in recovering from unusual flight attitudes that might occur as a consequence of severe turbulence such as that encountered in the wake of a large aircraft. Powerful vortices can be experienced when encountering wake turbulence, which can roll aircraft beyond 90 degrees of bank (even to inverted) and result in extreme pitch attitudes. Pilots trained in aerobatic flight have a greater chance of successfully recovering from such a situation without damaging the aircraft or impacting the ground. Many airline companies are sending their pilots to unusual attitude and aerobatic training, to enhance these skills and thereby reduce risk, and many general aviation pilots seek such training for similar reasons (1).

Aerobatic Maneuvers

Aerobatic maneuvers are essentially based on and permutations of the roll and the loop. A roll involves a continuous change in bank through 360 degrees generally about the longitudinal axis of the aircraft or at least about the direction of flight. A loop involves a continuous change in pitch, through 360 degrees, usually in a vertical direction. There are many variations of rolls and loops and in combination these constitute most of the aerobatic maneuvers commonly used and seen. Aerobatic maneuvers are characterized according to G forces as well. "Inside" aerobatic maneuvers involve keeping the aircraft in a $+G_z$ environment throughout the maneuver (see also Chapter 4). The traditional loop, begun from upright flight with a pull back on the control stick, is an example of an "inside" maneuver (Figure 27-1). "Outside" aerobatic maneuvers involve keeping the aircraft in a $-G_z$ environment throughout the maneuver. The outside loop, begun from inverted flight with a push forward on the control stick, is an example of an "outside" maneuver (2) (Figure 27-2).

Types of rolls include the aileron roll (along the long axis of the aircraft, usually begins with a pitch-up) (Figure 27-3), the barrel roll (a simultaneous roll and pitch such that the aircraft flies through a helical pattern), the snap roll (an accelerated stall and horizontal spin), and the slow roll (roll while the aircraft remains in straight and level flight). A particularly beautiful rolling maneuver is the rolling 360 (the aircraft flies in a 360-degree horizontal turn while continuously rolling). Looping maneuvers include the (normal) circular loop and the square loop. Maneuvers that require looping and rolling include the avalanche (involving a snap roll, from inverted to inverted, at the top of a loop), the horizontal eight, the Cuban eight, the vertical eight, the cloverleaf (involving four loops in sequence with 90-degree vertical rolls separating the loops), the Immelmann (a half loop with a half roll to upright at the top of the loop), the split–S (a half roll to inverted flight followed by a half loop), and the vertical S.

Most of the looping aerobatic maneuvers, and some of the rolling maneuvers, can be performed as "inside" or "outside" maneuvers. Most pilots find outside maneuvers to be more technically challenging to perform, as well as being more uncomfortable due to the $-G_z$ forces experienced (see also Chapter 4).

It is important to note that "outside" maneuvers are almost the sole purview of civilian sport and competitive aerobatic flight. Military aerobatic flight, expressed as air combat maneuvering, occurs almost exclusively in the $+G_z$ arena, with the exception of achieving transient zero G flight to increase airspeed. Few military pilots have chosen to exploit outside maneuvers, finding it quicker and more effective to remain in $+G_z$ flight domains.

Civilian Aerobatics

Aerobatics are performed in the general aviation arena for purposes of pilot proficiency, unusual attitude training, recreation, competition, and for demonstrations and air shows. Aerobatic pursuits range from the weekend general aviation pilot performing limited maneuvers to highly skilled aerobatic pilots competing and performing in large air shows. The International Aerobatics Club, a division of the Experimental Aircraft Association (EAA) that advocates and fosters all aspects of aerobatics with an emphasis on safety, has developed categories of aerobatic pilots, based on skill levels, for purposes of competition. Competitive categories start with basic and proceed through sportsman, intermediate, advanced, and unlimited. Basic aerobatics include $+G_z$ maneuvers such as upright spins, aileron rolls, and loops. Maneuvers become more complex as one goes through the categories, with $-G_z$ maneuvers becoming

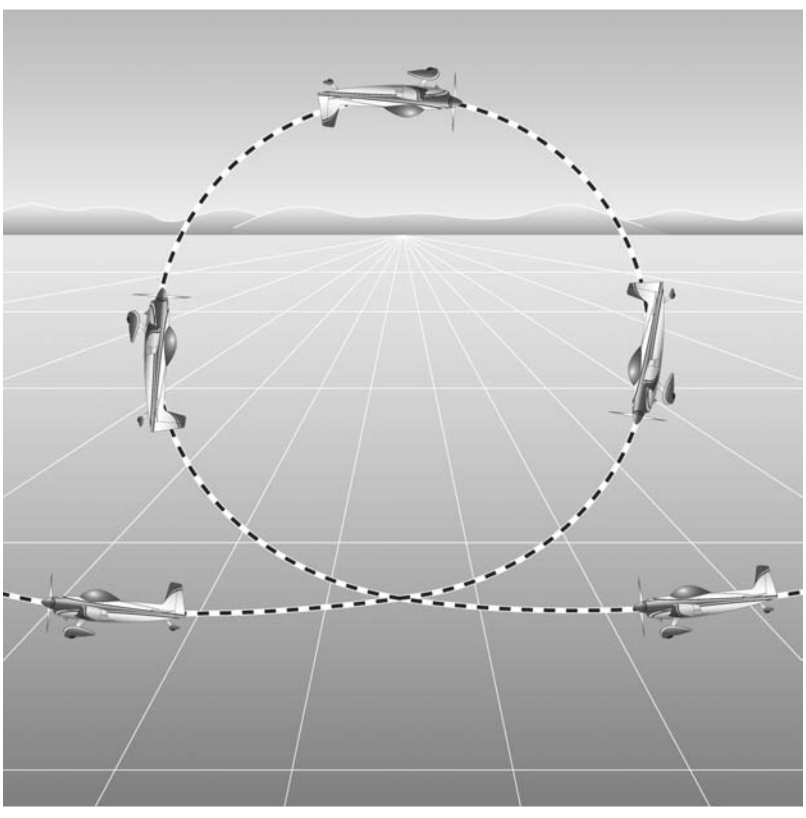


FIGURE 27-1 The inside loop, involving continuous $+G_z$ exposure. (Adapted from Robson DR. *Skydancing: aerobatic flight techniques.* Newcastle: Aviation Supplies & Academics, 2000.)

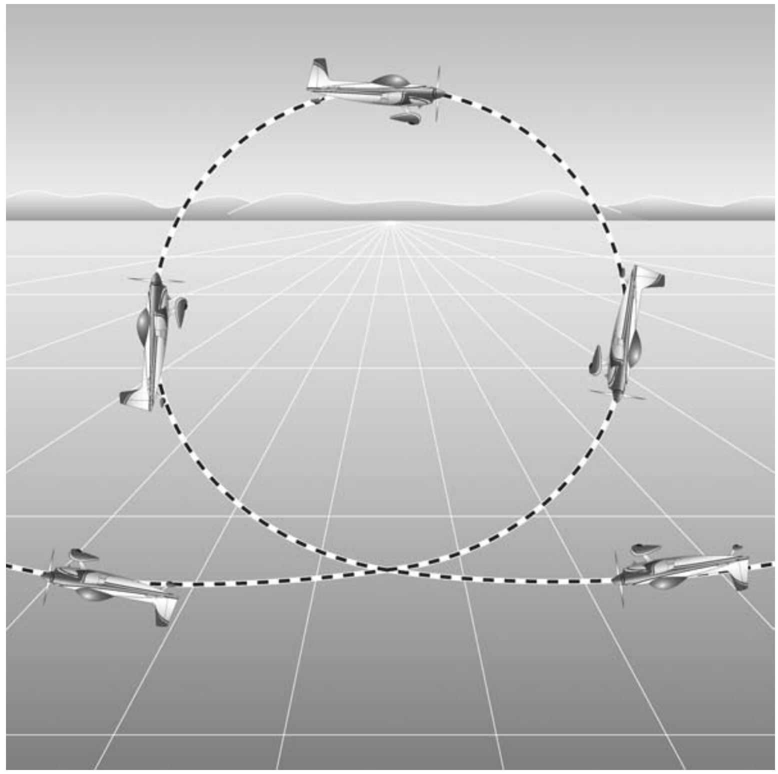


FIGURE 27-2 The outside loop, involving continuous $-G_z$ exposure. (Adapted from Robson DR. *Skydancing:aerobatic flight techniques.* Newcastle: Aviation Supplies & Academics, 2000.)

more prevalent in the advanced and unlimited categories. Aerobatic maneuvers, if performed properly and within the design specifications both of the maneuver and the aircraft, are not in and of themselves dangerous. However, if aerobatic maneuvers are performed improperly, if pilots are not appropriately trained and experienced, or if they have underlying physiological compromise, aerobatic maneuvers can result in significant risk. Overstressing an airframe or a pilot during aerobatics can and has resulted in catastrophic failure of either or both.

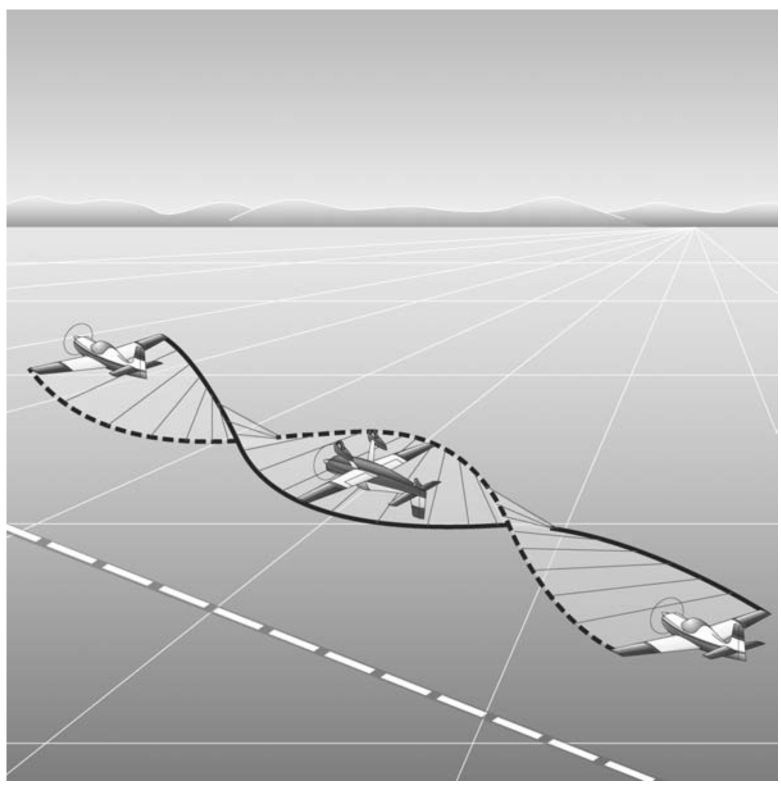


FIGURE 27-3 The Aileron roll. (Adapted from Robson DR. *Skydancing:aerobatic flight techniques.* Newcastle: Aviation Supplies & Academics, 2000.)

The Physiological Challenges of Aerobatic Flight

Aerobatic flight involves rapid movement through all spatial planes in a controlled manner with resultant rapid changes in gravitational force vectors and in sensory input. This presents a very challenging environment with potential severe impact on neurologic, sensory, and cardiovascular systems (3). Gravitational forces are primarily in the G_z axis, with some G_x and G_y components in various maneuvers. For example, brisk linear acceleration experienced during an afterburner-assisted takeoff in a fighter aircraft or during a catapult shot from an aircraft carrier, induces $+G_x$, and snap rolls in general aviation aerobatic aircraft produce highly transient G_y exposures. The preponderance of force experienced in civilian aerobatic flight, however, remains both $+G_z$ and $-G_z$. The detailed physiology of sustained acceleration is covered elsewhere in this textbook (see Chapter 4), so this chapter will concentrate on the specific gravitational forces and physiological effects experienced and reported by aerobatic pilots, especially in the civilian aerobatic sector.

The information presented in this chapter is, for the most part, based on data gathered at the 1996 National Aerobatic Championship competition at Fond-du-Lac, Wisconsin and at the 1996 Aerobatic World Championship competition in Oklahoma City, Oklahoma. Questionnaires as to the effects of aerobatic flight experienced were distributed and accelerometer readings were taken at the cockpits of competitive aircraft on landing immediately after competitive routines. The respondents were mostly advanced or unlimited aerobatic pilots.

Civilian aerobatic pilots generally wear parachutes, but employ no $+G_z$ protective equipment during flight. Restraint systems are typically of the five-point type, including a $-G_z$ strap, and some seat belts are equipped with rachet devices to further enhance stability in the seat. Some pilots reported participating in weight training and aerobic conditioning to assist their $+G_z$ tolerance. Positive G_z protection includes muscle tensing and wide variations of the semiclosed glottis-straining maneuver, with no standardized training across the sport. There are no protective maneuvers for $-G_z$, but pilots reported that relaxation and adaptation with practice were helpful in minimizing untoward effects due to $-G_z$ exposure. G_z levels experienced in civilian aerobatic flight are well into the ranges where untoward physiological effects may be seen. The Super Decathlon 8KCAB, an aerobatic aircraft designed primarily for training and $+G_z$ maneuvers, has aerobatic load limits of +6 and −5 g. The Pitts S2-C aircraft, commonly used for training, air shows, and advanced aerobatic competition, also has aerobatic load limits of +6 and −5 g. The Extra Aircraft 300L, designed for air shows and unlimited aerobatic competition, has flight load limits of +10 and −10 g, and the Sukhoi SU-31 has aerobatic load limits of +12 and −10 g.

Any of these aircraft are capable of achieving and sustaining G_z maneuvers that place pilots in an environment where all reported untoward $+G_z$ effects. They are also capable of achieving extreme $-G_z$ environments that represent hitherto largely unexplored flight regimes that will not be duplicated in any other aeronautical endeavors.

Positive G_z Effects

Advanced and unlimited aerobatic competitors and aerobatic air show pilots average peak +8 G_z exposures (peak +12 G_z recorded), with vertical turns producing the highest $+G_z$ loads. Duration of exposures in these maneuvers range from 1.5 to 3 seconds, with turns executed rapidly and precisely. Pilots report a full range of $+G_z$ effects, with more than 70% experiencing tunnel vision and gray-out (loss of peripheral vision), 30% reporting blackout (loss of vision), and 20% reporting at least one episode of G-induced loss of consciousness (G-LOC). G-LOC was experienced more commonly in aerobatic training aircraft, which are flown in lower G_z flight profiles (4–6 peak $+G_z$) but sustain the acceleration longer. Pilots agreed that the 3-second or less duration of exposure in advanced aerobatics was the primary protection against G-LOC. Other $+G_z$ effects included skin rashes, back, neck and arm pain, headache, transiently decreased hearing, bright scotoma, muscle cramps, difficulty breathing, and urinary incontinence. Positive G_z tolerance increased with practice and repeated exposure.

Negative G_z Effects

Advanced and unlimited aerobatic pilots average peak −8 G_z exposures as well (peak −10 G_z recorded), again with vertical turns producing the highest loads. Duration of exposures was similar to the $+G_z$ regime. Approximately 60% of aerobatic pilots report headaches with $-G_z$ exposure, especially early in the aerobatic season. Forty percent report bloodshot eyes, especially early in the aerobatic season, consistent with conjunctival petechial hemorrhaging. Red-out, a phenomenon that has never been adequately explained but may be due to gravitational effects on lower eyelids, was reported by 10% of pilots. Other $-G_z$ effects included bright scotoma, red scotoma, eyelid rashes, eye pain, fatigue, and persistent vertigo in a few cases. This persistent vertigo, known as the *wobblies* amongst aerobatic pilots, is typically sudden in onset, can be near incapacitating in flight, and persists for days, weeks, or longer after onset. This entity, recently described as *G-induced vestibular dysfunction* (GVID), most closely resembles benign paroxysmal positional vertigo (BPPV) in its clinical expression (4). Its underlying pathology is most likely similar to that which occurs in BPPV, first described by Epley (5). Free-floating otoconia or cupular crystals are thought to migrate into the posterior semicircular canal, producing a false sense of angular motion with resulting vertigo and nystagmus with head movement in certain planes. Treatment with various modifications of the canalith repositioning procedures first described by Epley has been very successful in the treatment of BPPV (6). In GVID, liberation of otoconia and subsequent migration to the posterior semicircular canal would be precipitated by shear forces induced by wide excursions in positive and $-G_z$ exposure, accounting for the persistent vertigo characteristic of the disorder. Further research, including identification of cases of GVID and therapeutic trials of canalith repositioning, needs to be done.

The push–pull effect deserves special mention in the context of civilian aerobatics. Civilian aerobatic pilots have recognized since the early 1980s that $+G_z$ tolerance is markedly reduced immediately following a $-G_z$ exposure. Civilian aerobatic competitions have strongly discouraged or prohibited $+G_z$ maneuvers immediately following $-G_z$ exposures (without a short recovery period in the program) for over two decades, significantly antedating cognizance of this dangerous paradigm in the military and broader aeromedical communities (see also Chapter 4).

Fatigue, hydration status, and thermal stress are also important considerations and areas where risk can be increased in aerobatic flight if these stressors are not mitigated. G tolerance is reduced by all these factors. Most aerobatic aircraft have bubble-type canopies, and aerobatic competitions and air shows generally occur in the spring, summer, and autumn months. Temperatures in cockpits can be quite high, especially during ground operations and while waiting to takeoff. Adequate cockpit ventilation, hydration, rest, and conditioning are essential protective measures to observe in aerobatic operations.

Aerobatic Accidents

Every year there are accidents involving aerobatic aircraft, usually during practice or during air shows. Air shows pose the greatest risk because maneuvers are conducted at lower altitudes, at times only feet from the ground. Accidents generally involve loss of situational awareness and/or spatial orientation, with resultant collision with the ground or, in formation aerobatics, with another aircraft. Occasionally, airframe failures occur as well. Rarely, physiological compromise may be a contributing factor. The following accident report excerpts from the National Transportation Safety Board (NTSB) database typify aerobatic accidents.

A. ***NTSB Identification: IAD96FA126*** On August 4, 1996, approximately 6.37 PM eastern daylight time, an Aerotek, Pitts Special S-1S, N2HT, was destroyed when a wing failed while performing aerobatics at the Three Rivers Regatta, and impacted in the Ohio River in Pittsburgh, Pennsylvania (7). The certificated commercial pilot/owner received fatal injuries. Visual meteorologic conditions prevailed and no flight plan had been filed for the local flight conducted under 14 Code of Federal Regulations (CFR) Part 91.

   The pilot took off from Allegheny County Airport at 6.15 PM. After a period of holding, the pilot received clearance into the Regatta Aerobatic Box. A videotape taken of the accident showed the maneuvering by the pilot for the planned initial maneuver, a double snap roll. Within seconds of the beginning of the video, the lower left wing and a portion of the top wing failed. Both failed wings were seen folded aft against the empennage as the airplane descended and impacted the water inverted.

   Witnesses interviewed after the accident and who knew the pilot stated that the pilot had told them that he used airspeeds higher than the manufacturer's recommended maneuver airspeeds to obtain better performance from the airplane. Witnesses stated that they looked in the airplane on various occasions and saw higher positive and negative flight load factors than recommended by the manufacturer indicated on the load meter in the cockpit. "Witnesses acknowledged that the pilot voiced his concern to acquaintances about the airplane's wings, and had purchased a set of wings for the airplane, because he had experienced flutter during recent flights."

B. ***NTSB Identification: NYC07FA007*** On October 14, 2006, approximately 1.00 PM eastern daylight time, an Extra Flugzeugbau Gmbh 300, N168EX, was destroyed when it impacted terrain at Culpeper Regional Airport (CJR), Culpeper, Virginia (7). The certificated commercial pilot was fatally injured. Visual meteorologic conditions prevailed, and the airplane was not operating on a flight plan. The local air show flight was being conducted under 14 CFR Part 91.

   According to an FAA inspector who had been attending the show, the pilot had been performing aerobatic maneuvers for approximately 6 to 7 minutes along runway 04–22 when the accident occurred. At the time of the accident, the pilot was performing "multiple snap rolls on a 45-degree down line," and during the maneuver, the inspector heard the announcer state that the airplane was in "the fourth turn of a five-turn demonstration." The inspector also noted the altitude of the airplane in reference to the ground and shouted "NO," as he "did not believe the aircraft could make another turn and clear the ground."

   A review of video footage revealed that the airplane completed two left-turning rolls at an approximately 45-degree descent angle, but during a third roll the trajectory changed toward a vertical descent. Following that, three additional left rolls were also completed in an approximately vertical-descent trajectory. After recovering from the last roll, the airplane stabilized in an estimated 45-degree nose-down, 20-degree left-wing-down attitude. The airplane continued to descend, and as a distant tree line came into the camera's view, the airplane's nose began rising, to where it was nose-level when the airplane impacted the ground. The airplane then disappeared into a depressed area behind the runway.

C. ***NTSB Identification: MIA98FA135A*** A flight of four airplanes were participating in an air show. The flight leader of the demonstration team stated they had just completed an arrowhead formation (7). The number 2 and 3 airplanes moved into the diamond formation. The flight team completed the 5/8 loop portion of a 1/2 Cuban eight, set the 45-degree inverted downline, completed a

1/2 roll to the upright position, and was beginning the entry into a "clover" loop, when the accident occurred. Witnesses and video from TV stations indicated that the flight leader, number 3, and number 4 airplanes started pulling up out of a dive to initiate the diamond "clover" loop, when the number 2 airplane continued to descend and collided with the number 4 airplane. The NTSB determines the probable cause(s) of this accident as follows: the failure of the number 2 airplane pilot to maintain visual contact and/or proper position/clearance from other aircraft.

These NTSB reports all describe fatal accidents involving highly experienced civilian aerobatic air show pilots with many years of experience. There have also been catastrophic air show accidents involving military jet aircraft, some with massive fatalities on the ground as well, such as the Ramstein Air Show disaster of 1988, which caused more than 500 casualties among those in attendance (8). The failures to remain within human or aircraft performance limits or a moment's lapse of concentration are commonly fatal errors in the unforgiving pursuit of air show aerobatics.

Civilian aerobatic air show pilots typically wear Nomex fire retardant gloves and flight suits to afford some protection in a potential postcrash environment. Some aerobatic competitors also use Nomex garments, but many do not. The use of helmets is rare in civilian aerobatics. An important recent innovation in civilian aerobatics is an ejection seat system designed and employed in Sukhoi aerobatic aircraft. The ejection system is pneumatically powered, involves immediate and automatic parachute deployment, and can ensure survival at speeds as low as 70 km/hr and altitudes as low as 15 m.

Aerobatic flight is thrilling to watch, exhilarating to perform, and enhances airmanship and pilot safety. Aerobatic flight can also subject pilots and aircraft to extreme gravitational exposures, spatial disorientation (SD), and loss of situational awareness, with potentially tragic results. The world of civilian aerobatics, with $-G_z$ exposures that cannot be duplicated in any other sport or activity, certainly provides opportunity for interesting study of both short- and long-term physiological effects. Opportunities to interact with and study these unique pilots and their environment should be pursued by interested practitioners and researchers in the field of aerospace medicine.

AERIAL APPLICATION OPERATIONS

Unique Aspects of Aerial Application Flights

Aerial application is the delivery of substances, usually liquid chemicals, from the air to the surface of the Earth. The most common type of aerial application is the spraying of herbicides, pesticides, or fertilizers for agricultural purposes, commonly known as *crop dusting*. (Initially, most pesticides were applied in powder, or dust form, hence the term *crop dusting*. Now, most applications are liquid spray and *aerial application* is the preferred term.) Other forms of aerial application include the application of fire suppressants ("fire bombing"), mosquito control, and the application of herbicides for the purpose of eradicating plants used for illegal purposes (counterdrug activities).

From an aeromedical standpoint, this type of flying creates health concerns in several different areas. The low altitude of operations (sometimes only feet above the ground), rapid acceleration required during maneuvering, long duration of duty days, heat stress, and exposure to potentially dangerous chemicals are the primary hazards associated with this type of flying. Night application involves increased risks of obstacle contact. Secondary hazards include smoke exposure (fire fighting), lack of pilot redundancy, proficiency issues, and in the case of counterdrug operations the possibility of surface-to-air weapons discharge. Because these activities seldom involve the carriage of passengers and the operations usually take place in relatively unpopulated locations, the risk for casualty is limited primarily to aircrew. However, inadvertent misapplication of chemicals due to winds (overspray) or pilot miscalculation represents a potential hazard to collateral crops, livestock, or even humans.

The first recorded aerial application occurred in 1906 when John Chaytor used a tethered hot air balloon to seed an area of swampland in New Zealand. The first use of an airplane to perform aerial application occurred in 1921 when a modified Curtis Jenny was used to spread lead arsenate near Troy, Ohio to control sphinx moth caterpillars. In 1922, cotton fields in Louisiana were dusted to kill boll weevils. The first commercial crop dusting operation began in 1923 by a company that eventually became Delta Airlines. Aerial application of agricultural chemicals steadily became more common in the United States during the 1930s and 1940s, but the post–World War II period was the peak of activity as small family farms began to be amalgamated into much larger farming operations. It was during this time that aircraft were manufactured specifically for aerial application. In the late 1960s, however, environmental concerns resulted in increased regulation and a decline in the number of aerial applicators. Currently, there are somewhat more than 2,000 aerial application companies in the United States.

The first use of aerial fire-fighting in the United States occurred in 1930 when a Ford Tri-Motor aircraft dropped a load of water in a wooden beer keg. In 1955, a Boeing Stearman dropped six loads of free-flowing water on a fire in California.

Types of Aircraft

Almost any type of aircraft can be modified for aerial application. The most common types, however, are specifically designed single-seat fixed-wing aircraft, modified biplane aircraft, modified multiengine aircraft, and rotorcraft.

The advantages of a specifically designed aerial application aircraft include rugged construction for high-G tolerance and superior crashworthiness, high power-to-weight ratio that allows better maneuverability and load capacity, high-lift wing design allowing lower-speed application, and better visibility for the pilot. The disadvantages include higher cost and lack of utility for nonaerial application activities.

The advantages of a modified biplane include the relatively lower cost, high-lift wings, good visibility, and some utility in nonaerial application activities. The disadvantages include the need to modify the aircraft, an open cockpit that could increase the pilot's exposure to the chemical being applied, and decreased crashworthiness.

The modified multiengine aircraft (used for aerial fire fighting) has a vastly superior delivery capacity, greater utility in nonaerial application activities and usually has the advantage of multiple crewmembers. The primary disadvantages are the significantly increased cost (both of acquisition and operation) and generally higher operational altitudes required by its decreased maneuverability.

Rotorcraft provides exceptional maneuverability and outstanding visibility, but this is counterbalanced by a somewhat diminished delivery capacity and relatively high cost.

Training Issues

Aerial applicators are required to hold a commercial pilot certificate and have additional training in aerial application. This additional training is acquired through schools specializing in agricultural aviation and augmented by on-the-job training with experienced aerial applicators. The aerial applicator must also be trained for and successfully obtain a Commercial Pesticide Applicators license.

Low-Altitude Activities

Most aerial application takes place as close to the ground as possible. This insures maximum delivery of chemical to the intended site with minimum overspray (the application of chemicals to unintended sites). Obviously hypobaric medical problems are usually not a concern; however, the risk of contact with obstructions is significantly increased in low-altitude operations. The pilot's attention during these operations must be split between the need to assure that the aerial application is proceeding properly and the need to be vigilant for obstructions. This creates a high task load that requires the pilot to be at peak performance for an extended period of time. As a pilot reaches the end of a pass over the delivery site, he must discontinue the application and rapidly gain altitude to avoid obstructions that might include fences, roads, buildings, power lines, or rising terrain. If the operation requires multiple passes, he must then turn the aircraft as efficiently as possible, rapidly return to, and level off at delivery altitude, while avoiding the obstructions and reactivating the application. All of these activities must take place in a matter of seconds.

Clearly, any medical condition that impairs a pilot's ability to make rapid judgments and react instantly has the potential to be catastrophic. Although sudden medical incapacitation is always a small risk, fatigue, distractions, medications, and alcohol are much more likely to affect the pilot's ability to perform at low altitude. It is critical that the pilot assess himself before and during each flight for any suggestion that he is not at the "top of his game" and then adjust his operations accordingly.

Acceleration Exposure

The efficient application of spray requires rapid changes in aircraft direction and altitude over short geographic distances. The result is exposure to high G loads, both by the aircraft and the pilot. It is routine for crop dusters to pull 2 to 4 G_s dozens of time daily in low-altitude situations in close proximity to obstructions. Most exposures are $+G_z$. (see also Chapter 4). Although this level of G exposure is unlikely to impair trained healthy individuals, it can be more problematic under certain circumstances. Clearly repeated G exposure leads to fatigue that can then diminish G tolerance. The so-called push-pull phenomenon, such as might occur when an airman pushes over an obstruction and then pulls up close to the ground to begin a spraying pass, can also decrease G (see also Chapter 4). Aviators who are under treatment for hypertension can be subject to decreased G tolerance from medication effects. Overexposure to chemicals used for spraying, especially organophosphates, can impair the sympathetic nervous system to the point of diminished G tolerance. In all these circumstances, the effect on G tolerance can lead to reduced cerebral perfusion with accompanying impairment of cognitive and visual ability. This is likely to be more problematic as dusk approaches late in the workday.

Prolonged Crew Duty Day

Most aerial application operations occur in time-critical situations. Obviously in fire fighting operations, the more retardant that can be delivered, the quicker the fire can be contained. This may mean long days of flying as many missions as possible to maximize the delivery of retardant. Similarly, crop dusting must be accomplished during a relatively small "time window of opportunity" when the growing conditions are right for the delivery of chemicals. A busy crop dusting service will have many fields over a wide geographic area to spray during this period of time, so sunrise to sunset operations 7 days a week is the rule. Clearly, a series of long duty days leads to accumulating fatigue and could potentially increase the risk for inattention to tasks.

Heat Stress

With the exception of certain fire fighting and night operations, aerial application takes place during daylight hours, mostly during the spring and summer growing seasons when it is not raining. This means that the pilot is exposed to warm weather and direct sunlight. When this is combined with low-altitude operations and slow flight, which limits the flow of cooling air through the cockpit, there is a significant risk for heat stress (see also Chapter 7). The use of air-conditioning in some aircraft helps counter this risk, but many crop dusting aircraft do not have this option available. It is critical that aircrew stay well hydrated during warm weather operations. Unfortunately, some pilots are reluctant to drink extra fluids because that leads to the need to urinate that often requires shutting down the operations.

Exposure to Chemicals

The most potentially hazardous chemicals used in agricultural aerial application are organophosphorus compounds. Organophosphates are pesticides that work by irreversibly blocking acetyl cholinesterase. The result is unabated cholinergic neuromuscular activity. This is the desired effect in agricultural pests, but humans are subject to the same toxicity with a sufficiently acute exposure. Indeed, some of the most common military nerve agents are organophosphates. Aerial applicators are exposed to these substances when they are mixed and loaded, while they are being delivered, and when the aircraft is cleaned up after spraying. Symptoms of acute poisoning include diaphoresis, lacrimation, salivation, gastrointestinal cramping, and bronchospasm. Left untreated, central nervous system stimulation with seizures and respiratory failure can develop. A recent study (9) has suggested a significant correlation between chronic low-level organophosphate exposure and chronic neurologic symptoms, including fatigue, depression, absentmindedness, and difficulty concentrating. Clearly, these are symptoms that cannot be tolerated in aerial applicators. There was a lower correlation of these findings with other pesticides, herbicides, and fungicides.

Most Common Contributing and Casual Factors in Accidents

As one might expect, aerial application accidents are much more likely to occur during the application-related operation itself, rather than on takeoff or landing. In fact, 62% of aerial application accidents occur during the maneuvering part of the flight compared with 9% for general aviation accidents (10). Because most of this flying is at relatively low speeds and altitudes, crash survival is easily possible with good aircraft design. Modern aerial application aircraft incorporate several features to increase survivability, including roll cages, five-point restraint systems, crushable fuselage components (including floor and landing gear), engine mount design that pushes the engine down and under the cockpit in a head-on collision and a lack of protruding, noncollapsible objects in the cockpit.

LIGHTER-THAN-AIR OPERATIONS

The first lighter-than-air (LTA) vehicle dates back to the Montgolfier brothers whose hot air balloon first successfully carried Jean-Francois Pilatre de Rozier and Marquis Froncois d'Arlandes on November 21, 1783 in Paris, France. That flight was quickly followed by the flight of Jacques Charles who flew in a balloon filled with LTA hydrogen gas. In 1785, de Rozier flew a third type of balloon, a combination hot air and hydrogen balloon. It was designed with a hydrogen envelope inside a hot air envelope. Unfortunately, the combination of highly flammable hydrogen gas with an ignition source resulted in an explosion that killed both de Rozier and his passenger. The Roziere combination balloon was ignored until nonflammable helium gas became more easily available (see also Chapter 1).

Balloons have served a variety of purposes over time. Balloons were used as battlefield observation platforms reporting enemy troop positions and directing the artillery fire as early as the French Revolution. Zeppelin airships were used by the Germans in World War I to make occasional bombing raids on targets in Great Britain and to transport heavy loads over long distances. Airships were used during World War II for search and rescue, photographic reconnaissance, convoy escort, and antisubmarine patrols. Balloons have also been used to gather scientific information on the upper atmosphere. Currently ballooning is primarily a sport activity in the United States. Airships are used commercially primarily for advertising or television photography of sporting events. They are also used in border patrols and fire observation (11–14).

Types of Lighter-than-Air Vehicles

There are several types of LTA vehicles: hot air balloons, cold air or gas balloons, combination balloons, and airships. These are termed *lighter-than-air* because they are buoyant. How that buoyancy is achieved depends on the type of vehicle. Balloons consist of a bag, called the *envelope*, from which a basket, or gondola, is suspended. The gondola carries the heat source that is usually fueled by propane. In hot air balloons, buoyancy is achieved by heating air in the balloon envelope allowing the gas to expand and become less dense. The less dense air is LTA outside the balloon and the balloon therefore rises.

Cold air balloons have the same components as hot air balloons except for the lack of a heat source. The envelope, however, is sealed at the bottom. In cold air balloons, buoyancy is achieved by filling the balloon envelope with a type of gas that is LTA, thereby causing the balloon to rise. Hydrogen, helium, and ammonia have been used as lifting gases. When helium became more easily available, interest increased in the Roziere combination balloon. Currently, Roziere balloons use a helium inner envelope surrounded by a hot air envelope heated by propane. This type of balloon was used by Steve Fossett to fly solo around the world in 2002 (15).

There are three classes of airship—rigid, semirigid, and nonrigid. The current airships, or blimps, are typically of the nonrigid type, also called *pressure airships*. These airships have a large envelope that contains the lifting gas. Air-filled bags, called *ballonets*, are located inside the envelope, and act as ballast regulating the internal pressure. The ballonets deflate or inflate with air as the helium expands on ascent and contracts on descent. The airship also has a gondola for carrying the passengers, crew, and cargo with gasoline-powered engines on either side. The flight control surfaces (rudder, fins, and elevators) provide stability and the ability to steer the vehicle.

Semirigid airships, like the new Zeppelin NT (Neue Technologie) airships, are pressure airships that have a lower rigid keel structure. The rigid airships, like the old Zeppelins, initially had a metal framework containing a gas-filled bag. The Hindenburg fire, however, essentially ended the use of the rigid airship.

Special Nature of Lighter-than-Air Flying

In hot air balloons, lift is controlled by changing the temperature of the air inside the envelope. To ascend, the air is heated more. To descend, the air in the balloon is allowed to cool naturally for a slow descent, or air is released through a parachute vent at the top of the balloon for a more rapid descent.

Directional control in a balloon is very limited—the balloon is dependent on the direction of the wind. Because wind direction and speed varies depending on the altitude, the balloon pilot can change the direction of the balloon by changing altitude. One of the difficulties with flying a balloon is dealing with the delayed response in slowing or stopping a descent. Stopping a descent can take more than 30 seconds from the time the burner is lit until the descent stops. The pilot, therefore, needs to plan carefully.

Airships have more directional control because they are powered by engines and have flight control surfaces. On takeoff, the airship pilot vents "heavy" air from the ballonets to make the airship positively buoyant. The pilot will also use the engine and elevators to angle the blimp into the wind to provide additional lift. By filling the ballonets with air and adjusting the elevators, the airship pilot descends. This again requires careful planning on the part of the pilot to avoid being "too light" on landing.

Environmental Exposure Considerations

Balloons and airships typically operate at relatively low altitudes. Hypoxia and trapped gas problems are rarely an issue. Heat or cold exposure may, however, be an issue and appropriate clothing for the weather should be worn. Windchill is not typically a factor because the balloon moves with the wind.

Ballooning is very weather dependent and typically requires clear skies and calm winds. Storms, with the possibility of lightning strikes, are extremely dangerous for balloons. Rain can also decrease visibility and even damage the balloon envelope. Balloons typically fly early in the morning just after sunrise, or late in the day just before sunset, to ensure winds are calmest.

Airships can fly in more weather conditions than balloons. With its slow speed and responsive controls, the airship can typically handle turbulence better than an airplane. Icing is also less of an issue than with an airplane. Airships are capable of flying in all the weather conditions that a fixed-wing aircraft can; however, airships must avoid takeoff or landing in wind speeds greater than 30 knots.

Personal Protective Equipment

Some personal protective equipment is recommended for balloon pilots. To protect the balloon pilot from burns in dealing with the heat source, flame-resistant gloves should be worn such as leather or nomex gloves. The pilot's clothing should include long sleeves and long pants and be made of nomex or natural fibers that will not burn readily. In addition, the pilot should wear eye protection (may simply be sunglasses) to shield the eyes from heat should a gust of wind blow flames toward him or her. Balloon systems that hang the burner from the envelope instead of supporting it in the basket would require helmets be worn by the pilot and passengers. The ground crew also should wear gloves whenever handling the ropes or lines to prevent rope burns.

Accident Data

A review of the NTSB accident database for balloon accidents from 2005 to 2006 revealed 20 accidents involving 92 persons (16). Sixty-three of the 92 individuals were uninjured, 10 suffered minor injuries, 16 suffered serious injuries, and 3 were fatally injured. Two of the fatalities were due to the basket being engulfed in flames after collision with power lines. The other fatality was due to collision with boulders on top of a hill. Although the injuries were not always specified in the report, most serious injuries involved fractures (arms, ankle, pelvis, vertebrae, and clavicle). Two of the serious injuries involved ground crewmembers. In one case, the ground crewmember became entangled in the balloon vent lines and was lifted off the ground as the balloon ascended to approximately 75 ft. The pilot was unable to lose altitude because of the entangled vent lines. While attempting to get the ground crewmember close to a tree, the balloon struck the tree; the crewmember became untangled and fell through a barn roof. In the other case, the ground crewmember grabbed onto the basket of the balloon as it landed. The ground crewmember slipped on wet grass and continued to hold onto the basket as the balloon lifted into the air again. When the balloon reached approximately 8 ft in the air, the grip on the rope was lost and the crewmember impacted the ground.

Human error was listed as a probable cause of the accidents in 70% of the cases. Wind (high winds, wind gusts, downdrafts, and wind shear) was listed as a cause or contributing factor in 11 of the 20 accidents (55%). Fourteen of the 20 accidents (70%) occurred during landing with 10 of those resulting in serious injuries. This is consistent with other studies of balloon accidents. De Voogt and van Doorn reviewed balloon accident data from 2000 to 2004 (16). During this 5-year period, 86 accidents occurred with 85% of the accidents occurring during landing procedures. Fifty-eight percent of those involved in the accidents were uninjured, 23% suffered minor injuries, 18% were seriously injured, and 1% were killed. A review of hot air balloon accidents in the United Kingdom from 1976 to 2004 again revealed that most accidents occurred during the approach and landing phase of flight with adverse weather present in a number of the accidents (17).

A review of the NTSB accident database for airship/blimp accidents from 2002 to 2006 revealed three accidents and one incident involving a total of seven persons (18). Six of the seven individuals were uninjured and one suffered minor injuries. There were no serious injuries or fatalities. Seventy-five percent of the accidents/incidents were caused by human error. Weather and winds were also a factor in three of the four accidents/incidents. Similar to the balloon data, the majority (75%) of the airship accidents/incidents involved the landing phase of flight. In one accident, the pilot encountered weather and downdrafts, lost control of the airship and collided with trees and transmission wires. In another accident, the airship was "very light" during the landing. The accident occurred as the pilot attempted to abort the third landing attempt and impacted a fence and a lumber pile. The one incident occurred as the crew was securing the airship after landing. A wind gust blew the airship into nearby trees. The remaining accident occurred during the takeoff phase of the flight. A wind gust blew the ship to the right. The ground crew manning the nose ropes could not control the movement. The pilot attempted takeoff, but the landing gear hit a fence and then the airship settled onto a one-story building. A second wind gust pushed the airship into the next building over.

Crashworthiness

The design of the hot air balloon with its wicker basket gondola provides little in the way of crash protection. The limited directional control in a balloon also makes crash avoidance more challenging. Despite these issues, the accident data shows that the vast majority of individuals involved in balloon accidents are either uninjured or suffer only minor injuries.

The airship's construction and control systems make it very safe to operate. All of the individuals involved in the airship accidents discussed previously were either uninjured or suffered minor injuries. Because the pressure inside the airship envelope is very low (~1/15 psi), a small hole in the envelope would cause the gas to escape very slowly taking hours or even days to affect the airship's performance. A large hole in the envelope would likely abort the mission, but would still allow the airship plenty of time to return to its base for the needed repairs.

LTA operations offer a unique aspect of aviation with slow speeds and quiet operations. LTA pilots are not required to hold a medical certificate. Despite having little medical oversight, however, preexisting medical issues were not found to contribute to any of the accidents reviewed.

ULTRALIGHT OPERATIONS

Ultralight aircraft are defined by the Federal Regulations under Part 103—Ultralight Vehicles (19). These vehicles are, except for the purpose of instruction, intended to be manned by a single occupant, used for sport or recreational purposes, weigh less than 155 lb (70.3 kg) if unpowered and less than 254 lb (115.3 kg) if powered. If the vehicle is powered, it is not to have a fuel capacity of more than 5 gal. These weight limits do not include floats or safety devices, such as a ballistic parachute, which are intended to be deployed in a potentially catastrophic situation. Ultralight vehicles are also limited to a full power speed in level flight of not more than 55 knots (101 km/hr) calibrated airspeed and a power off stall speed that is not to exceed 24 knots (44 km/hr) calibrated airspeed. Ultralight vehicles and their component parts are not required to meet the same airworthiness certification standards specified for aircraft or to have certificates of airworthiness (20).

Types of Ultralight Vehicles

Ultralight operations include aircraft in the following categories: glider or sailplane, motor gliders, paragliders (Figure 27-4), motorized paragliders, hang gliders, balloons, and ultralights.

Limitations to Operate Ultralight Vehicles

The operators of ultralight vehicles are not required to meet any aeronautical knowledge, age or experience requirements, or to have a medical certificate to operate this class of vehicles (20). Although the operators of ultralight vehicles are not required to hold a valid medical certificate to operate this class of vehicles, they must still comply with the part of the CFR that cover the certification of pilots, flight instructors and ground instructors, specifically, Part 61.53 Prohibition of operations during medical deficiency (21). CFR Part 61.53 states that a person may not act as pilot in command while that person is known to have a medical condition that would make the person unable to operate the aircraft in a safe manner (21). The operator of an ultralight vehicle, who does not possess a valid medical certificate but possesses a valid U.S. driver's license, must comply with each restriction and limitation imposed by that person's U.S. driver's license and any judicial or administrative order applying to the operation of a motor vehicle (22). Operators are not subject

FIGURE 27-4 Training paraglider making a pass over Torrey Pines California. Photo courtesy of Dr. Arnold A. Angelici, Jr.

to the restriction that applies to sport pilots; the ultralight operators do not have to be eligible for a medical certificate. CFR Part 103.7(b) Certification and Registration does not state that if they have been denied a medical certificate they cannot operate their vehicles. Nothing is mentioned in CFR Part 103 about restrictions if they were previously denied a medical certificate, nor is anything mentioned about requiring the operator to have a valid U.S. driver's license, as long as they comply with Parts 61.23(b) 61.53(b), and they are able to operate the vehicle in a safe manner.

Other limitations to the operation of ultralight vehicles include the hours of operation and where they can be operated. Ultralight vehicle operations are restricted to the time between sunrise and sunset. If the vehicle is equipped with an appropriate anticollision lights, the time of operation can be extended to 30 minutes before sunrise and up to 30 minutes after sunset. All ultralight vehicle operations are restricted to uncontrolled airspace and are not to be operated over congested areas of a city, town, or settlement (23,24). The flight visibility in uncontrolled airspace, at or below an altitude of 1,200 ft above the ground level (AGL), must be 1 statute mile and clear of clouds. If the ultralight vehicle is flying more than 1,200 ft AGL, the visibility must be 5 statute miles or greater (25). Operators of ultralight vehicles are also expected to follow the same general operating rules and regulations governing all other aircraft. These include operations in controlled airspace and, restricted airspace, flight restrictions in the proximity of areas designated by notice to airmen (NOTAM) (25).

Personal Protective Equipment

The type and amount of personal protective equipment will vary depending on the vehicle flown. Open structure vehicles, such as paragliders, motorized paragliders, or hang gliders would require, for safe operation, that the operator wear helmet and goggles for head and eye protection. Clothing should cover the arms and legs, along with gloves and shoes, to provide protection from windblast, temperature extremes, and airborne particles such as insects or debris carried aloft by thermals or other weather phenomena. The clothing may be made of fire-retardant material if the vehicle is powered; the possibility of fire exists because of fuel carried and a source of ignition is present. Safety belts, four- or five-point type seat belts for upright seated vehicles, or a harness for prone, "weight shifting controlled" vehicles, should be installed and used with the intention of protecting the operator from injury due to sudden acceleration or deceleration forces that were or were not intended to be experienced by the operator. Parachutes have been recommended to be worn in all sailplanes and gliders (Figure 27-5). There are two types of parachutes, the type worn by the operator of the vehicle and the other is an airframe parachute. The airframe parachute system, introduced in the early 1980s, is attached to the ultralight's airframe. If there is a need to utilize the parachute because of structural failure or unrecoverable loss of control, the parachute is deployed and the operator remains with the ultralight vehicle throughout the recovery. Some of these systems are referred to as *ballistic recovery* systems because the parachute is deployed using an explosive or a compressed air charge (26). The structure surrounding the operator of the vehicle is also part of the crash protection and is intended to absorb some of the impact forces experienced on landing with the parachute.

FIGURE 27-5 Single place paraglider launching off the bluff at Torrey Pines California. Note the seat pack parachute. Photo courtesy of Dr. Arnold A. Angelici, Jr.

Accident and Incidents Data Involving Ultralight Vehicles

Incidents or accidents involving ultralight vehicles are not investigated by the NTSB. The responsibility of the FAA is to determine if the operation of the ultralight vehicle was within compliance of the Federal Regulations, and the accident is delegated to an inspector assigned by the Flight District Office manager where the accident occurred (27). The NTSB continues to report the probable causes of the accidents that involve this class of aircraft. At the time of this writing there were 191 accidents in this class since 1980, with 93 accidents involving 102 fatalities. Most of these fatal accidents had some component of pilot error that led to the accident. An article by Pagan reviewed ultralight accidents reported in the NTSB database from 1985 through 2004. He concluded that pilots with less than 40 hours in make/model-specific flying hours were significantly more likely to be involved in a fatal crash. Pilots with more than 40 hours in make/model-specific flying hours were more likely to crash due to maintenance-related problems such as engine failure (28). Schulze and Ricther, in 2002, reviewed all paragliding accidents that occurred in Germany from 1997 through 1999 to determine the trends in injuries related to paragliding (29). They analyzed information from 409 accidents during this period and found that there were a decreasing number of accidents involving paragliders and the most common injury types were spinal injuries. The most common cause of an accident was the deflation of the glider (32%), followed by oversteering (14%), collision with obstacles (12%), takeoff errors (10%), landing errors (13%), misjudgment of weather conditions (5%), unsatisfactory preflight checks (5%), midair collisions with other flyers (2%), accidents during winching (2%) and defective equipment (<1%). Of the injured pilots, 40% had logged less than 100 flights. An emergency parachute was used in 39 of the accidents; 10 pilots were seriously injured (26%) and there were 3 fatalities. Gauler et al. published retrospective analysis of 41 patients who suffered spinal cord injuries after paragliding accidents. The case records of the 41 patients spanned a 10-year period. They found that the most frequent site of fractures occurred in the thoracolumbar region, with L1 being the most frequent vertebrae affected (30%) (30). In 2000, Schulze et al. examined the data from accidents that involved 55 male and 9 female pilots treated for paragliding accidents (31). They found that 62.5% suffered spinal injuries and 18% pelvic fractures. Fifty-four percent of the injuries left the pilots with persistent functional disabilities and complaints. The main causes of most of the accidents in this study were due to pilot error in the handling of the paraglider or the general lack of knowledge of the risk factors. The phase of flight where the injuries occurred was 46% during the landing, 43% during flight, and 11% during the takeoff phase. In another study of paragliding performed in remote areas, Fashing et al. noted that most of the injuries occurred either during takeoff (42%) or in-flight (44%). All but three accidents were attributed to pilot error (32). Injury to the spine was diagnosed in 34 of the 43 cases and 85% involved vertebral bone fractures. Thirty-eight pilots had injuries to the extremities, 7 suffered multiple traumas, and 17 incurred head trauma. No fatalities were reported in this study, but 14 pilots suffered permanent damage to joints or nerves.

Injury and Accident Prevention

Most investigators noted that improved training programs should be introduced to prevent injuries that were noted to occur due to the operator's unfamiliarity with the equipment. Some suggested utilizing safer, simpler gliders for beginners and intermediate level pilots, and improving pilot skills through graduated performance and safety training (33). To reduce spinal injuries, some investigators have noted a reduction in the frequency of these types of injuries after back protectors or padded back protection was introduced to the operators (31,33–35). None of the studies reviewed suggested that any of the accidents that occurred were due to a preexisting medical condition. Although there is no medical oversight, the possibility of accidents due to pilot medical conditions remains small. This could be attributed to the relatively younger age of the participants of this type of activity (mean age: 30 years) compared with the average age of the certificated pilots who fly general aviation aircraft (mean age: 47.7 years) (33,36). The operations of ultralight vehicles are not without risks. Proper training, use of appropriate protective equipment, and adequate preflight planning can minimize the risks inherent to the operation of the ultralight vehicle.

LIGHT SPORT AIRCRAFT OPERATIONS

On July 16, 2004, Federal Aviation Administrator Marion C. Blakey signed the "Certification of Aircraft and Airmen for the Operation of Light Sport Aircraft Rule," which became effective on September 1, 2004 (37). This marked the culmination of a 9-year effort by aviation advocacy organizations, notably the Aircraft Owners and Pilots Association (AOPA) and the EAA, to revitalize the "grass roots" segment of the general aviation industry (38,39). Rising fuel prices, increasing cost of new and used aircraft, increasing costs associated with aircraft maintenance and flight training, and limits placed on the aging active pilot population by medical certification requirements were all motivating factors for aviation advocacy groups to seek light sport rulemaking. The light sport rules afford distinct advantages to pilots in each of these areas of concern.

Light sport aircraft are limited in weight, performance, and configuration. Maximum takeoff weight can be no more than 1,320 lb if the aircraft is intended to operate from land and 1,430 lb if operated from water. Airspeed is limited to 120 knots, and stall speed must not be more than 45 knots at the aircraft's maximum weight. Light sport aircraft can have no more than two seats, and they must have fixed landing gear (light sport seaplanes can have retractable gear), a single, reciprocating engine, and a fixed or ground adjustable propeller. Light sport aircraft cannot be pressurized (40).

Certificated pilots can fly light sport aircraft, if they have the appropriate category and class ratings, without further training. Training requirements for individuals seeking sport pilot certification include a minimum of 20 hours of total flight time, with 15 hours of flight training from an instructor and 5 hours of solo flight. An individual seeking certification as a sport pilot must pass a knowledge test and a practical test. Sport pilots cannot fly for hire or compensation, at night, in instrument conditions, in class A airspace, or in class B, C, or D airspace without specific training and a logbook endorsement from an instructor. Sport pilot instructor requirements are also much less rigorous. At a minimum, potential light sport instructor pilots must hold a sport pilot certificate, receive logbook endorsements and pass appropriate knowledge and practical tests, and have 150 hours of pilot-in-command time (40).

Maintenance and inspection requirements for light sport aircraft are streamlined as well. Instead of extensive and time-consuming training to receive airframe and powerplant ratings, as well as Inspector, aircraft ratings, the rule allows light sport aircraft owner inspection and maintenance with as little as 16 hours of training for inspections and 120 hours of training for maintenance (40).

Perhaps the most interesting, profound, and attractive (to pilots) feature of the light sport aircraft rule concerns medical certification. Medical self-certification is the cornerstone of the medical aspects of the sport pilot rule. Pilots must self-certify from a medical perspective, and assure that they do not operate their light sport aircraft if they know or have reason to know of any medical condition that would make them unsafe to do so (41). The rule makes it clear that the determination of whether or not a pilot has a medical condition that renders them unsafe to operate their aircraft is the sole responsibility of the pilot, in consultation with a personal physician as appropriate. Pilots may use a current and valid U.S. driver's license as evidence of medical certification, provided the applicant has not been denied at least a third-class FAA medical certificate, their most recent FAA medical certification has not been suspended or revoked, and a previously granted special issuance has not been withdrawn (42). This caveat concerning previous FAA medical certification has drawn a great deal of criticism from aviation and pilot advocacy groups, who expected the rule to allow a valid U.S. driver's license to serve as evidence of medical certification without regard to previous denial or revocation of FAA medical certification. Efforts are underway by advocacy groups to urge the FAA to revise the sport pilot/light sport aircraft rule accordingly (38,39).

Therefore the overall effect of the sport pilot/light sport aircraft rule has been dramatic from the perspective of general aviation. An entire fledgling industry has grown up around light sport aircraft, with many new domestic and internationally based companies producing certificated light sport aircraft as well as experimental aircraft kits. Lower fuel consumption, the ability to use automobile fuels, lower maintenance costs, and medical certification aspects all work to the advantage of this segment of aviation. Many aging pilots, who could not previously afford to continue recreational flying activities or could not maintain medical certification are now continuing or reentering general aviation. Many pilots who could maintain FAA medical certification through special issuance, but did so at considerable personal expense for required medical testing on an annual basis (especially for cardiac-related special issuance) are choosing to exercise privileges under the sport pilot/light sport aircraft rule and avoid further application for FAA medical certification.

While the revitalization afforded the general aviation industry is laudable, there are obvious health and safety concerns attending the sport pilot/light sport aircraft rule. Lessening of maintenance and pilot training experience requirements have the possibility of increasing mishaps related to both pilot judgment and error, and to aircraft maintenance. Medical self-certification, although in principle is exercised every time an individual pilot operates an aircraft, can also result in an increased risk with regard to accidents from pilot incapacitation or medical compromise. Most recent aircraft accidents are the result of errors in pilot judgment, decision making, or execution, with a minority of accidents due to mechanical failure (43). Similarly, 2% or less of aircraft accidents are caused by medical reasons. The sport pilot/light sport aircraft rule has been in effect only for 3 years. Aviation advocacy groups are already citing the success of this rule, especially the medical self-certification aspects, in promoting the revitalization of general aviation. Time will reveal the impact of the sport pilot/light sport aircraft rule with regard to health and safety. Data on light sport aircraft accidents must be gathered for several years and compared to accident data from the general, light aircraft aviation sector. If accident data are not substantially worse, aviation advocacy groups can be expected to be strong proponents of even less regulatory control, extending medical self-certification, and possibly more lenient maintenance certification requirements, to heavier and more powerful general aviation aircraft. The sport pilot/light sport aircraft rule may prove to be a powerful force in keeping general aviation viable in the United States; however, the potential impact to aircraft mishaps is yet to be determined.

HELICOPTER OPERATIONS

Unique Aspects of Helicopter Flight

Helicopters provide a unique complement to aviation operations, being able to perform numerous functions not readily accomplished by fixed-wing aircraft. Helicopters vary in size and configurations, with the ability to provide such functions as low-level reconnaissance flights, search and rescue, fire bucket operations, rescue hoist operations, personnel and patient transport, and equipment transport. In the military, helicopters provide these functions as well as target acquisition, close to medium-range interdiction attack, and sling-load operations. Helicopters generally operate at lower altitudes and airspeeds, without supplemental oxygen, and with less acceleration exposure. These may be the only airborne vehicles during low-ceiling and/or visibility weather conditions. Helicopter operations may occur in both visual flight rules (VFR) and instruments flight rules (IFR) conditions. Helicopters have the ability to land and takeoff from areas with minimal space for a landing zone and do not require a runway.

Helicopters produce lift through a set of rotating airfoils, or rotor blades. The rotor system consists of the central hub with two or more blades attached to it. As the blades travel through the air, lift is produced in the same manner as a fixed wing. The airflow over the blades of the rotor system produces a pressure differential directed in the plane perpendicular to the axis of rotation. The amount of lift is changed by varying the pitch angle of the rotor blades. This can occur either equally on all blades resulting in an increased lift vector, or variably among the individual blades that causes a tilting of the rotor system resulting in directional flight. This feature provides the pilot with complete control of the lift developed by the rotor blades as well as the direction in which the lift is directed.

Most helicopters are configured with a single main rotor system for producing lift. The rotor system is turned by the main mast directly from the transmission. As the rotor turns in one direction, the aircraft fuselage tends to rotate in the opposite direction. This rotation, or torque effect, changes with engine power changes. As engine power is increased to the rotor system, fuselage rotation also increases. As power to the rotor is decreased, torque effect is decreased. The usual method of counteracting torque in a helicopter with a single main rotor system is by the use of an antitorque rotor mounted on the tail. The tail rotor is mounted perpendicular to the axis of rotation for the main rotor system. Just as with the main rotor, the tail rotor produces varying lift, or thrust, depending on the pitch angle of the blades. Tail rotor thrust is varied through the use of foot pedals much like the rudder pedals in a fixed-wing aircraft. The tail rotor pedals also control the heading of the helicopter while at a stationary hover. However, some helicopters such as the Sikorsky CH-46 Sea Knight and CH-47 Chinook have two main rotor system configurations and are called *tandem rotor helicopters*. These helicopters have counter-rotating main rotor systems that do not produce the torque effect. As a result, there is no need for an antitorque tail rotor.

The cyclic pitch control system provides the means of controlling the forward, aft, and lateral movements of the helicopter (44). The helicopter will advance in the direction of cyclic stick movement. Moving the cyclic stick fore or aft results in the nose of the aircraft pitching down or up. Movement of the stick laterally will move the helicopter right or left during a hovering flight and generate a rolling motion during forward flight. This movement is the result of a differential pitch angle between the individual blades of the main rotor system as they move through the plane of rotation. Control inputs in tandem rotor helicopters produce similar results, but by a slightly different manner.

The collective pitch control system (collective) provides vertical control of the helicopter. Movement of the collective is sent through a series of controls to the main rotor and simultaneously changes the pitch of all the blades. Raising the collective increases the pitch angle of the main rotor blades and lowering the collective results in a decrease in pitch angle.

Unique Aspects of Vibration Exposure

Helicopters utilize a rotor system to produce lift and directional control. There are three design types of systems used in helicopter rotors. The semirigid rotor system resembles a seesaw, and is usually used on helicopters with two rotor blades. The blades are rigidly mounted to the hub, which is able to tilt about the top of the mast. When one blade moves downward, the other moves up. The articulated rotor system uses hinges to attach each rotor blade to the hub. The hinges allow for independent movement of each rotor blade. Articulated blades can move up and down (flapping), back and forth in the horizontal plane (leading and lagging), and can change pitch angle independently. The hingeless rotor system functions like the articulated system, but uses elastomeric bearings instead of hinges to allow for flapping and lead–lag movements of the blades.

All three rotor system designs allow the rotor blades to flap up and down as they rotate. As the advancing blade rises, there is a reduction in the angle of attack, thereby reducing the lift produced by that blade. The retreating blade is allowed to settle causing an increase in the angle of attack and a greater amount of lift. Decreasing lift on the advancing blade and increasing lift on the retreating blade compensates for the differences in the lift produced over the rotor disc halves that results from the difference in relative wind speeds. Blade flapping creates an unbalanced condition resulting in vibration. To minimize the development of these vibrations, drag hinges are used in articulated rotor systems that allow the blades to lead and lag. Regardless of the rotor system design or configuration, helicopters generate vibration forces.

These vibration forces create potential health concerns for the rotorcraft occupants. These include such issues as impaired physiologic functions, worsened fatigue, reduced physical performance and coordination, impaired cognition, back and other musculoskeletal pain, and vision disturbance (see also Chapter 5). Helicopters contain multiple sources of vibrations. The internal sources include the engines, transmissions, main and tail rotor systems, auxiliary power units (APUs), and electrical generators. Each of these produces a unique frequency range, all of which can affect human physiologic function and performance. Vibration intensities tend to increase when transitioning from a hover to directional flight, with increases in airspeed, and with increasing aircraft weight or loads.

Unique Aspects of Noise Exposure

Helicopter crewmembers are regularly exposed to equivalent noise levels of greater than 85 dB, with some helicopter cockpit and cabin noise levels exceeding 100 dB. Noise exposure to 85 dB equivalent sound level is generally recognized as the threshold for potential health risks (see also Chapter 5). In addition to rotor and engine noises, radio and intercom communication systems can easily increase noise level to an additional 5 dB. Helicopter noise is characterized by a broad spectrum of frequencies, peaks, and durations. Noise can cause temporary or permanent auditory and nonauditory effects depending on the duration and intensity. Auditory effects include temporary threshold shift and permanent sensorineural high-frequency hearing loss. Nonauditory effects of noise may include fatigue, annoyance, behavioral changes (irritability), attentiveness, problem solving, performance, reading comprehension, memorization, and interference with communications (45).

Unique Aspects of Spatial Disorientation

Spatial orientation is defined as the natural ability to maintain body orientation in relation to the surrounding environment at rest and during motion (see also Chapter 6). SD is a condition in which a pilot's perception of direction does not agree with reality. SD is the most common cause of human-related aircraft accidents, and occurs when the aviator fails to sense correctly the position, motion, or attitude of his aircraft or of himself relative to the surface of the Earth and the gravitational vertical plane. Helicopter pilots are susceptible to the same SD issues and illusions as experienced by airplane pilots. Two surveys concerning SD in U.S. Army rotary-wing operations were conducted by the United States Army Aeromedical Research Laboratory (USAARL), Ft Rucker,

TABLE 27-1

Army Accident Classification

Accident Class	*Definition*
A	An Army accident in which the resulting total cost of property damage is $1,000,000 or more; an Army aircraft or missile is destroyed, missing, or abandoned; or an injury and/or occupational illness results in a fatality or permanent total disability.
B	An Army accident in which the resulting total cost of property damage is $200,000 or more, but less than $1,000,000; an injury and/or occupational illness results in permanent partial disability, or when three or more personnel are hospitalized as inpatients as the result of a single occurrence.
C	An Army accident in which the resulting total cost of property damage is $20,000 or more, but less than $200,000; a nonfatal injury that causes any loss of time from work beyond the day or shift on which it occurred; or a nonfatal occupational illness that causes loss of time from work (e.g., 1 work day) or disability at any time (lost time case).

Alabama. The survey of aviation mishaps showed that 30% of class A to C accidents involved SD as a significant factor (Table 27-1).

The survey of the general aircrew population showed that 78% of military aircrews have been disoriented at some time during flight and 8% felt that SD caused symptoms to the extent that flight safety was threatened.

Ninety percent of the information used to maintain orientation with surroundings comes from the eyes. The visual system is the most reliable of the senses and normally overrides input from the vestibular and proprioceptive system in the case of conflicting inputs (see also Chapter 6). The vestibular system, consisting of the otolith organs and semicircular canals in the inner ear, provides secondary orientation input to the brain. The third system which provides orientation input to the brain is the pressure-sensing proprioceptive system. The proprioceptive system includes nerves in the skin, muscles, joints, and internal organs that sense surface pressure, tension, and stretch differentials. While on the ground, the vestibular and proprioceptive systems provide minimally used input to the brain for orientation. However, during flight these systems play a more active role in sensing body position and orientation. These are referred to as the *seat-of-the-pants sensations*, which, when coupled with the visual inputs, may result in positional sensory mismatch and ultimately SD.

There are several factors that make helicopter flying more conducive to the development of SD. Helicopters are unique in their mode of flight. They tend to fly closer to the surface of the Earth than most airplanes normally operate. These flight operations may occur during low-ceiling or poor-visibility weather conditions. The most common phase of flight associated with disorientation accidents is the approach to landing.

The major factors that increase the chances for developing SD include flight in poor visibility and the loss of visual cues. This can be due to adverse weather conditions such as fog and precipitation, or may be the result of brown-out (caused by dust) or white-out (caused by snow) conditions produced by helicopter rotor wash. Standard helicopter flight instrumentation tends to be less robust than in many airplanes, and may be inadequate for flying under certain operational conditions.

Disorientation accidents occurred much more often at night than during the day. More than 40% of all SD-related accidents in the USAARL study occurred during flight using night vision devices (NVDs). Aviation personnel must be familiar with visual illusions that may affect safe flight, as they can lead to the development of SD. There are several visual illusions that are more closely associated with helicopter operations.

The waterfall effect illusion occurs when hovering or in slow flight at low altitudes over water with minimal references. The downward motion of water particles in the rotor wash creates an illusion that the aircraft is climbing. If this illusion remains unnoticed, lowering the collective by the pilot to stop the perceived climb will cause the helicopter to descend from a stationary hover into the water.

The Wave Drift Illusion occurs while hovering over tall grass or water at night with minimal references; the motion of waves blowing out or away from the aircraft creates an illusion of the aircraft drifting opposite the motion of the waves. The illusion causes the pilot to instinctively adjust the cyclic to drift with the motion of the waves and out of the stationary hover.

The Lack of Motion Illusion can occur during low-level flight operations. The lack of discernible terrain contrast may result in the perception of flying at a faster than interpreted airspeed, causing the pilot to increase airspeed unnecessarily. While at a hover without adequate visual references, the aircraft may start to drift without detection by the pilot.

The Crater Illusion can occur during NVD operations. Viewing the periphery of the infrared (IR) searchlight gives the illusion that flat terrain slopes upward. Viewing another aircraft landing using these lights can give the illusion that the observed aircraft is descending into a crater when it is actually in straight and level flight over flat terrain.

Flicker Vertigo is a rare event that results from a steady light flicker, at a frequency of approximately 4 to 20 cycles/s. This unusual pilot response to a light flicker can produce unpleasant and dangerous reactions in normal subjects including nausea, vertigo, convulsions, or unconsciousness. The mechanism of these reactions remains unknown.

Fascination or fixation is not unique to helicopter operations. However, due to close proximity to the Earth's surface of most helicopter operations, fixation or fascination has the potential for a worse outcome. Fascination is a condition in which the pilot fails to respond adequately to a clearly defined stimulus despite having all of the necessary cues present and the proper response available. The individual concentrates on one aspect of the total situation to such a degree that he rejects other factors in his perceptual field. Target fixation is a cause of military aviation accidents. The pilot becomes so intent on hitting the target that he fails to observe his altitude and sometimes flies the aircraft into the ground.

Personal Protective Equipment and Procedures

Similar to fixed-wing flight, helicopter operations require the use of personal protective equipment, measures, and procedures. Military flight crews wear flight helmets, equipped with acrylic visors, to provide safety to the head and eyes. Aviators use hearing protection in addition to helmets or headsets for hearing conservation. The recent advent of communication ear plugs (CEPs) aid hearing protection by providing a speaker system inside the foam core of the ear plugs. This allows for improved audio comprehension while attenuating outside noise. Most pilots fly in fire-retardant boots and Nomex flight suits and gloves. Military flight vests provide additional survival equipment to include emergency radio transmitters, signaling devices, first aid kits, survival knives, and rations. Fire extinguishers, first aid kits, and emergency egress items are part of the accessory helicopter equipment. Personal protective procedures complement personal safety and include crew and passenger briefs, review of emergency procedure protocols, and emergency egress plans.

Crash Survival and Worthiness Issues

Helicopter design advances have improved crash survival and crash worthiness. Thorough review of aircraft mishaps has led to continuous improvements in design. Seats are designed either with a crush box or to stroke downward on impact, thereby absorbing and attenuating G forces. These advances significantly reduce the risk of occupant spinal injuries. Seat harnesses are four- or five-point systems, consisting of lap belts and shoulder harnesses. These restraints are designed to lock on impact and hold the occupant firmly in the seat to reduce flail injuries. The Kevlar helmet shell with acrylic visor is designed to absorb impact forces to reduce injury to the head. Like automobile frames and body design features, the aircraft fuselage is designed to crush, absorb impact energy, and reduce G-force transfer to the occupants. Despite these improvements, helicopter crashes still occur and occupants may receive transmitted G forces beyond the ability of their bodies to prevent serious injury.

Emergency Evacuation Issues

An important part of preflight preparation includes crew and passenger briefs covering required immediate actions during emergency conditions and subsequent evacuation. If it is necessary to make an emergency landing, occupants are instructed to remain in the aircraft and delay evacuation until the rotor blades stop turning. In case of an aircraft fire, immediate evacuation is conducted. Helicopter rotors are high-inertia systems meaning the rotors will continue to rotate, much longer than airplane propellers, after power from the engines has been shut off. Evacuation needs to be accomplished while maintaining awareness of the turning rotor blades and the dangers of the tail rotor system. Egress along uneven terrain may significantly reduce ground clearance of the rotor system. Caution must be used to avoid blade strike injuries.

Due to the position of the main rotor system(s) relative to the fuselage, helicopters have a high vertical center of gravity. This characteristic predisposes them to rolling over. When a helicopter rolls over with engine power still applied and the rotor system turning, the blades make violent impact with the ground. These forces are transmitted back to the power train and often result in severe occupant injuries and aircraft damage or destruction.

The high center of gravity also affects emergency water landings. After the initial impact, the helicopter tends to roll laterally to an inverted position. This change in orientation, along with reduced visibility and risk of drowning, makes helicopter water landings uniquely dangerous. Military water survival training, consisting of helicopter dunker egress and emergency breathing device familiarization, attempts to eliminate drowning deaths in otherwise survivable emergency water landings.

Most Common Contributing and Causal Factors in Accidents

Human error is commonly cited as a definite causal factor in more than 80% of all aviation accidents. Other less frequently occurring factors are related to engine failure, maintenance deficiencies, and environmental conditions. The role of the flight surgeon in aviation mishap prevention and investigation focuses on reviewing and investigating the role of human factors involved in an accident. Human factors errors that may be responsible or contributory to an accident include issues such as inappropriate safety standards, inadequate training, ineffective leadership, and/or individual failure.

Numerous articles have been written and published that review aviation, and, specifically, helicopter accidents. The military services have several safety magazines that review and discuss the numerous aspects of flight and flight safety, to include reviewing aviation mishaps. The articles also provide descriptions of mishap-contributing factors and risk-reduction techniques. The U.S. Army FlightFax, U.S. Navy's Approach, as well as the United States Air Force's (USAF) Flying Safety Magazine and Torch magazines all focus on aircrew education, risk mitigation, and mishap reduction. As noted in the preceding text, SD is a prominent factor in aviation accidents. Other prominent factors that stem from SD include nighttime and NVD flight operations. Inadvertent flight into instruments meteorologic conditions (IMC) increases the risk of disorientation and mishaps. Flight operations in brown-out/white-out conditions, missed approaches on landing, and low-altitude/low-airspeed operations all increase the risk for mishaps.

A 2006 article in the Journal of Safety Research completed a review of the most common contributing factors for fatal and nonfatal civilian New Zealand helicopter mishaps (46). The researchers found, using multivariate logistic regressions, several statistically significant factors common to these mishaps. Postcrash fire and off-airport crash location significantly increased the likelihood of fatalities, although failure to obtain a weather briefing, air transport operations, and crash off-airport were the factors that significantly increased the likelihood of nonfatal injuries. Very few pilot or aircraft characteristics were related to the risk of fatal or nonfatal injury with crashes.

Other civilian studies involving mishaps of helicopter medical evacuation transport services have shown similar results. In one study, postcrash fire, bad weather, and night flying were significantly increased factors in fatal crashes (47). In another study, obstacle strikes during landing, bad weather conditions, and lack of discipline were factors involved with accidents (48). An Australian study found night flight to be a major risk factor for accidents (49). Crash-resistant fuel systems have been one remarkable safety change to reduce postcrash fires (50). These have been uniformly adopted in all types of military aircraft but with less, although slowly increasing, use in civilian helicopters.

SKYDIVING, PARACHUTING AND UNPOWERED PARASPORTS

The idea of using a device to slow the descent of a person falling to the ground seems to have originated in China as early as the 12th century. Leonardo da Vinci's famous drawings of a pyramid-shaped device made of linen and wood is the earliest known design of a parachute. The first "skydive" is widely accredited to the French physicist, Louis Sebastien Lenormand, who reportedly jumped from a tree while holding two parasols, but it was approximately 2 years later in 1785 that another Frenchman, J. P. Blanchard, constructed the first silk, nonrigid framed parachute. Reportedly, Blanchard successfully used the device to slow his descent after making an emergency exit from a damaged hot air balloon (51).

The modern origins of skydiving are typically traced back to Andre Jacques Garnerin who, beginning in 1797, made a series of parachute jumps from hot air balloons, one of which he performed from an altitude of more than 2,400 m. During his descent the parachute canopy oscillated so wildly that reportedly Garnerin became severely motion sick. In 1804, French scientist Joseph Lelandes introduced the concept of the apex vent, consisting of a circular hole in the center of the canopy, which helped to eliminate the problem of canopy oscillations.

The scope of modern parachute-based aerospace activities extends well beyond the origins of the parachute as a device to retard the fall of an object. The word parachute derives from the French language: *para*, meaning "defense against" or "shield", is joined with chute, meaning "a fall" and the resulting hybrid word literally translates as "that which protects against a fall." The origin of the word parachute is attributed to the aforementioned early French aviator Jean-Pierre-François Blanchard (1753–1809) (52).

The parachute is an integral component of a wide range of modern aerospace and terrestrial activities. The unifying feature of aerospace parachuting operations, or *parasports*, is that the final moments of each activity involve the participant(s) transitioning from aerial to terrestrial activities under a flexible fabric parachute canopy.

This section will consider the unpowered parasports skydiving or parachuting, and paragliding or parapente.

The terms *skydiving* and *parachuting* are usually applied to a subset of parasports that involve a person descending, from an aircraft or an elevated terrestrial location, and deploying a packed parachute to retard all, or only a latter component, of the return to Earth. The (Fédération Aéronautique Internationale) FAI Sporting Code (2006) (53) defines a parachute as "a collapsible device designed to counteract gravity using forces exerted on it by the air," a parachute jump as "a jump by a person from an aircraft of any kind, heavier or LTA, made with the intent of using a parachute for the whole or a part of the descent," a hang glider as "a glider capable of being carried, foot launched and landed solely by the use of the pilot's legs," and a paraglider as "a hang glider with no rigid primary structure." The FAI code does not include BASE (Building-Antennae-Span-Earth) jumping. The other main unpowered parasport, paragliding or parapente, involves a person launching, by foot, from an elevated terrestrial location under an already inflated parachute canopy (54).

This section does not consider parasailing or parascending, which involves a parachute-wearing participant being towed aloft by a motorized vehicle—often a powerboat; paraplane or powered parachute flight, which utilizes a motor to provide the thrust necessary for flight under a parachute canopy; hang gliding, which involves the use of a semirigid wing rather than a flexible fabric parachute; or *Trike* flight (powered hang glider), which involves a semirigid hang glider type of wing as well as a motor to provide thrust (see section **Ultralight Operations** earlier in this chapter).

The Special Nature of Skydiving

Modern unpowered parasports can be divided according to several factors. These factors include launch location (aircraft or ground-based) and/or altitude (low, medium, high or extreme), type of operations (civilian versus military), method of canopy deployment, and the type of parachute canopy used.

Launch Location: Aircraft or Ground-Based

A parachutist is able to launch from any elevated location that provides sufficient altitude for effective parachute canopy opening and adequate deceleration before landing.

A parachute jump can start from an aircraft (heavier than air, LTA, powered, unpowered) or from a terrestrial location (mountain peak, building, bridge etc.). A parachute jump that starts from such a terrestrial location is called a *BASE jump*. In this context, the term *BASE* is an acronym that refers to the types of locations from which these jumps are launched: **B**uildings, **A**ntennae (an uninhabited tower such as an aerial mast), **S**pans (a bridge, arch, or dome), and **E**arth (a cliff or other natural formation). The term *BASE jumping* is attributed to Carl Boenish (1941–1984) considered by many to be the father of modern BASE jumping. A paraglider flight commences either by launching from an elevated terrestrial location or by initially using a powered-winch to launch and terminates on successful return to a terrestrial location.

Launch Altitude: Low, Medium, High, or Extreme

Parachutists have launched from a height of less than 100 ft above ground level (AGL) (55) and from as high as an altitude of 103,000 ft above mean sea level (AMSL) (51,54,56). The low-altitude *pull-off* parachute launch was a spectacle practiced during 1950s air shows. The parachute canopy was deployed during flight and used to pull the parachutist off the aircraft. On August 16, 1960, during a USAF Aero Medical Laboratory mission code-named *Excelsior III*, Joseph W Kittinger (Captain, USAF) jumped from a helium balloon at an altitude of 102,800 ft (31,330 m) (57). He fell approximately 84,700 ft (25,820 m) before the automatic deployment of his main parachute canopy. Kittinger reached a speed of 614 mph at approximately 90,000 ft (27,400 m), which is often incorrectly referred to as his having broken the sound barrier during free fall (e.g., Guinness World Records 2006). The speed of sound at 90,000 ft is approximately 670 mph (1,078 km/hr).

Low-Altitude Parachuting

Although many BASE jumps are from low altitudes, it is unusual for civilian recreational parachuting to involve the deployment of a parachute canopy at a height of less than 2,000 ft AGL. BASE jumps utilize specialized equipment (e.g., parachute and jumpsuit) and typically involve predeploying a small drogue chute at the jump onset because the jumper does not attain a speed adequate for timely deployment of a conventional parachute canopy and because the jumper is falling in close proximity to a cliff-face or building/structure. Military parachutists, however, use low-level parachuting methods, often at night, to insert personnel into areas of combat operation. These low-level parachuting methods usually utilize static-line techniques to expedite the deployment of the parachute canopy. Paragliders either launch from ground level, albeit from elevated locations, or from 1,000 to 1,500 ft AGL during a winch launch.

Medium-Altitude Parachuting

The vast majority of civilian recreational parachuting involves a jump from an altitude of less than 20,000 ft AMSL and parachute canopy deployment from a height of greater than 2,000 ft AGL. These jumps do not require the use of oxygen during the free-fall or under-canopy phase although some of the higher-altitude record-breaking attempts (jumps from above 15,000 ft) utilize supplemental oxygen during the in-aircraft ascent to the jump altitude. BASE jumps routinely launch from altitudes greater than 2,000 ft AMSL, with modern record-attempt jumps launching from considerably higher altitudes. On August 26, 1992, Nic Feteris and Glenn Singleman climbed the *Great Trango* peak and then BASE jumped from the Northwest Face landing on the northern side of the Dunge Glacier. The jump was from an elevation of 5,955 m (19,537 ft) with a landing at 4,200 m (13,779 ft) for a vertical descent of 1,755 m (5,758 ft). On May 23, 2006, Glenn Singleman, Heather Swan, and others climbed and BASE jumped from the higher *Meru Peak* in northern India. This jump was from an elevation of 6,604 m (21,667 ft) with a landing at 4,850 m (15,912 ft) for a virtually identical vertical descent of 1,754 m (5,755 ft).

High-Altitude Parachuting

High-altitude parachute jumps, usually from altitudes greater than 20,000 ft AMSL, typically require the use of supplemental oxygen for a "prebreathe" period and/or during the descent phase of the operation. Military high-altitude parachuting operations (HAPO) include both high-altitude low-opening (HALO) and/or high-altitude high-opening (HAHO) missions. HALO operations entail prolonged free fall with late canopy deployment, whereas HAHO, which is typically reserved for more stealthy penetrations deep into denied territory, entails the early deployment of the parachute canopy and prolonged descent under canopy. There have also been occasional civilian recreational high-altitude parachute jumps from altitudes in the region of 25,000 ft AMSL.

Extreme-Altitude Parachuting

Parachute jumps from above Armstrong's line (the altitude at which, theoretically, the water in body fluids would boil at body temperature. Armstrong's line, or limit, is at ~63,500 ft AMSL where the atmospheric pressure is 0.0618 atm) are rare, in part because of the extensive (and expensive) equipment and logistic support that such a jump requires. During recent decades, several civilian teams have formed to attempt to exceed Kittinger's unofficial record jump from a helium balloon at 102,800 ft (31,330 m) (54,56–58). To date none of these attempts have been successful.

Kittinger's 1960 jump is not officially recognized, by the FAI, as a record because a small drogue canopy was deployed early during the free fall phase of the descent. The official parachuting altitude record is held by Yevgeny Andreyev who, in 1962, jumped from 80,325 ft (24,483 m) without the use of a drogue canopy to stabilize his free-fall. Andreyev's 1962 jump broke the, then, official record held by another RussianNikolai Nikitin who jumped from 46,965 ft in 1961 (56).

Civilian Parachuting

The diversity and scope of modern civilian parachuting are vast. Parachutists around the globe launch from aerial or ground-based locations to experience a variable period of free fall and descend to Earth under a deployed parachute canopy. A wide variety of activities may be undertaken during the free fall and under-canopy phases of a parachute jump. Some of the civilian parachuting variations include the following:

- BASE (**B**uildings, **A**ntennae, **S**pans, or **E**arth) jumping
- Free fall maneuvering, including acrobatics (free fall, style, free-flying, etc.) and efforts to reach high speeds during free fall
- Free fall formations of multiple parachutists [relative work (RW)] and under-canopy formations [canopy-relative work (CRW)]
- Free falling equipment variations, such as sky-surfing, where a modified snow board is used to "surf the wind" during free fall, and the use of wing suits or speed suits to increase the free fall glide ratio or terminal velocity, respectively
- Under-canopy maneuvering, including accuracy landings as close as possible to a specified target
- Passenger flights (tandem parachuting)
- Free fall and under-canopy photography and cinematography
- Professional civilian parachuting operations, such as placement of fire-fighting *smoke jumpers* or search-and-rescue personnel

A recent civilian adaptation, of the military use of parachutes to aid and/or retard the landings of aircraft, is the use of ballistic (forced deployment) parachute recovery systems for the safe recovery of aircraft from emergency situations (see also section **Ultralight Operations** earlier) (Figure 27-6).

Military Parachuting

Parachuting was adopted into military service very early in its modern development, and parachute operations are an integral component of virtually every national defense force throughout the world. Early in World War I, aerial observers, stationed in tethered kite balloons, were supplied with parachutes to allow rapid egress when their vulnerable and flammable observation platforms were attacked by fixed-wing aircraft or ground-based gunfire. Paradoxically World War I fighter pilots were not initially supplied with parachutes because, in part, of the weight and bulk of contemporary packed parachutes, and a mistaken view that having a parachute would interfere with the aggressiveness of the aircraft crew (59). The use of parachutes for troop placement commenced late during World War I and was substantially refined during and after World War II.

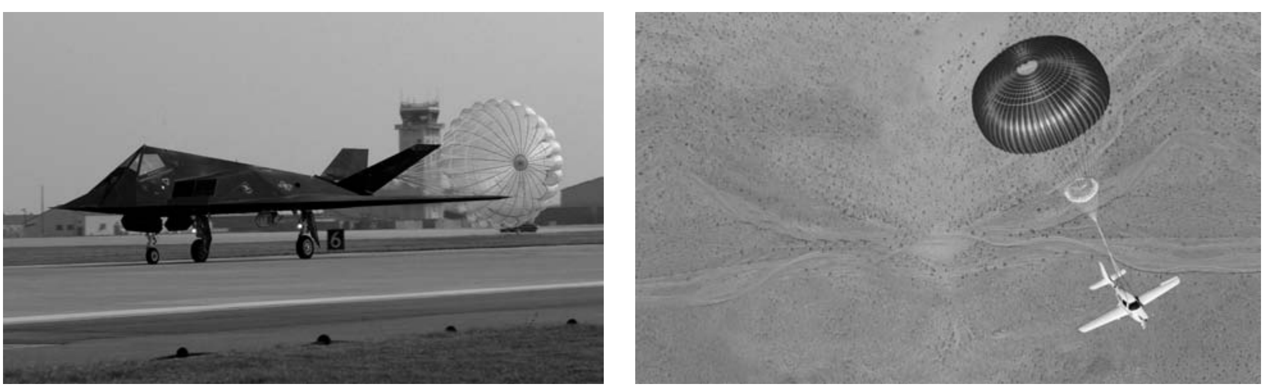
Modern military parachuting is almost as diverse as its civilian counterpart. The military use of parachutes (for carrying people) includes the following:

- Emergency ejection from aircraft
- Low- and midlevel parachute jumps to place personnel (small or large groups) into areas of operation (mass tactical operations)
- HAHO and HALO types of high-altitude parachute operations (typically employed by Special Operations Forces)
- Tandem parachuting operations to place non–parachute-trained personnel, or dogs, into areas of operation
- Demonstration team parachuting

Canopy Deployment: Before Flight or Before/After Reaching Terminal Velocity

A parachutist's canopy can be deployed before any free fall, early in the free fall phase before terminal velocity is reached, or after the parachutist reaches terminal velocity. In the context of parachuting, *free fall* refers to the falling phase of a parachute jump before the parachute canopy being opened. The forces acting on a free falling parachutist are due

A



B

FIGURE 27-6 Round parachutes assisting aircraft landing and emergency recovery. **A:** A U.S. Air Force F117 *Nighthawk* stealth fighter uses a round parachute to reduce its speed after landing and thereby reduce the runway distance taken to land. (USAF public information). **B:** Some modern civilian aircraft, such as this Cirrus SR20, use a large, forcefully deployed (ballistic), round parachute to provide safe recovery from in-flight emergencies (Cirrus Design Corp).

to gravity and air friction against their body, clothing, and equipment. In other contexts, the term *free fall* more correctly refers to motion where the only force acting is gravity such as space walking (or orbital extravehicular activity). The terminal velocity of a parachutist is the speed at which his/her weight (due to gravity) and air resistance (due to air friction) are equal, and the parachutist is no longer accelerating. For most tropospheric (the troposphere is the lowest and densest layer of the Earth's atmosphere containing ~75% of its mass as well as nearly all of its water vapor and *aerosols*) parachuting the free fall terminal velocity is approximately 120 mph (195 kph). Special free fall body positions and clothing allows free falling parachutists to reach terminal velocities in the range of 200 mph (320 km/hr). In 1960, Joseph Kittinger reached a terminal velocity of 614 mph (990 km/hr) during his stratospheric jump from 102,800 ft (31,330 m).

A paraglider pilot inflates his/her canopy while still on the ground (by either relying on natural airflow, perhaps assisted by the pilot walking or running into wind, or by the use of a winch) before commencing his/her flight.

A static-line parachutist has the canopy deployed automatically by means of a tethered *static* line that is connected to the aircraft and pulls the parachute from a pack on the jumper's back immediately on leaving the aircraft. The jumper experiences only a very brief free fall.

Many BASE jumpers never reach free fall terminal velocity and, because of this, require specialized parachute canopy and harness design to allow for safe openings at these lower speeds. Some BASE jumpers operate with such low height margins that they activate their drogue chute or feed-out their canopy as they commence their jump.

Most parachuting jumps involve the participant reaching terminal velocity in free fall before activating his/her canopy. For midaltitude jumps of less than 20,000 ft, this usually requires approximately 1,000 to 1,500 ft (or 10–15 seconds) in free fall for terminal velocity to be reached.

Types of Parachutes

Parachutes are usually constructed of a lightweight, strong, fabric canopy comprising "ripstop" nylon that is connected by a constellation of suspension lines, straps, and fittings to a harness assembly that contains and stabilizes the person, people, and/or load that is being carried. The suspension lines extend from attachment points on the canopy and are usually gathered through cloth loops or metal connector links at the ends of several strong straps called *risers*, which connect to the harness. Parachutes come in many shapes and sizes although most modern parachutes belong to one of two main categories: round and ram-air.

Round Parachutes

Round parachutes are classically dome-shaped structures with a semicircular, parabolic, or near-triangular vertical cross section. Unlike ram-air parachutes (see subsequent text), round parachutes do not typically generate significant amounts of lift but function primarily by generating sufficient drag to retard the speed of a falling person or object so that ground impact speeds are tolerable. Typically, a modern round parachute will allow a parachutist to descend at a relatively constant vertical rate of 10 to 15 ft/s; the final landing speed also being influenced by any horizontal drift occurring at the time of landing. Round parachutes are used in most forms of military parachuting (e.g., low-level static-line paratrooper operations), as well as numerous emergency (e.g., aircraft ejection seats and ballistic parachute aircraft recovery systems) and cargo applications. Round parachutes are rarely used in modern recreational/sporting skydiving, either as the main or reserve parachute. Early round parachutes were simple flattened hemispheres formed from a single layer of approximately triangular fabric pieces (or gores) sewn together. These parachutes suffered from instability due to irregular venting of the trapped air from under the parachute canopy during descent, and a significant absence of directional control. Modern round parachutes remedy these stability problems through a variety of design features, including the use of a less flattened and more conical–parabolic shape, the previously mentioned apex vent, and directional control through modifications of the basic canopy shape, often through sections being cut out of the canopy fabric (Figure 27-7).

Other variations of the round parachute design include annular, or ring, parachutes (basically round parachutes with a large circular hole cut out of the middle) and star parachutes (a round shape with four large triangular *pizza slices* cut from it). These more extreme round parachute variations are seen more often in cargo and motor sport applications than in modern aviation parachuting.

Ram-Air Parachutes

Most modern parachute jumps are made using ram-air parachute canopies that self-inflate to form an aerofoil or wing shape (parafoil) during deployment. Ram-air parachutes can produce significant amounts of lift, as well as drag, and provide greater degrees of stability, as well as speed and directional control, than round parachute designs.

Ram-air parafoils comprise two main fabric layers (upper and lower) that are connected by airfoil-shaped fabric ribs, or cell dividers, to form a series of spaces called *cells*. The front, or leading edge, of most of these cells is open (ports) and the trailing edge is closed. Many of the ribs are perforated with round holes (communication ports) that allow air to move between cells. In many designs, some of the end, or tip, cells, on each end of the parafoil, do not have open leading edge ports.

As the canopy deploys, air is forced, or *rammed*, into the open leading edge ports and inflates the cells. This increased air pressure equalizes throughout the parafoil, through the communication ports, which also allow any end cells to inflate. With the cells filled by the high-pressure ram-air, and restrained by the suspension lines connecting the canopy to the parachutist's harness, the canopy self-inflates on deployment and maintains an aerofoil shape. Different ram-air parafoil designs are used for different purposes. A

A B

FIGURE 27-7 Round parachute variations. **A:** A military static-line parachutist using a round canopy and carrying a pack of combat equipment suspended beneath. The round canopy design includes an apical vent, to improve stability, as well as several other openings to improve maneuverability and forward motion. (Photograph US Navy public information.) **B:** Round parachute canopies with apical vents being used in military parachuting. The apical vent provides some additional stability, but this canopy design offers limited forward motion and directional control. (Photograph US Army public information.)

ram-air paragliding canopy may be larger, have many more cells, and have more efficient lift–drag characteristics than a ram-air parachuting canopy that must also be able to reliably withstand the stresses of deployment at free fall terminal velocity (Figure 27-8).

Aeromedical Considerations of Parasports

The scope of parachuting activities is limited only by a few fundamental physical constraints (such as the laws of gravity) and the imagination and ingenuity of participants. Consequently the aeromedical considerations of parachuting are made up of issues that are both common to all forms of parachuting (e.g., the risk of lower limb injury during a landing), and specific to a particular activity subset (e.g., the risk of centripetal injury, resulting from very high speed spinning which can occur due, in part, to reduced air resistance during extreme-altitude parachuting). There is also a degree of overlap between the aeromedical considerations of the parasports and those of other groups of aerospace operations (e.g., paragliding and hang gliding).

Hazards of the Parachuting Environment

The diversity of unpowered parasports sees parachute pilots exposed to a wide variety of aeromedical hazards during their operations. These hazards include *altitude*—the effects of hypoxia, decompression illness (high-altitude parachuting), barotraumas (rapid descent), hypothermia, exposure to solar radiation, and so on; *acceleration*—the effects of opening shock, spinning (centripetal effect), and so on; *impact*—midair collisions, landing injuries, and so on; airblast—wind shear effects experienced during free-fall; *SD*; and *equipment malfunction*.

Hypoxia

Parasport participants are regularly exposed to altitudes above 10,000 ft AMSL. This exposure carries with it the risk of incapacitation or performance impairment due to hypobaric hypoxia (see also Chapter 2). Some parachuting activities, for example military parachuting operations and civilian tandem parachuting, also involve moderate levels of physical exertion that may act to potentiate the effects of hypobaric hypoxia. Frequently, military high-altitude parachuting involves the use of pressurized aircraft and the employment of self-contained supplemental oxygen for operations above 13,000 ft AMSL. Consideration for the addition of prebreathing 100% oxygen to decrease the risk of decompression illness increases with operations planned at altitudes above this elevation. Civilian recreational parachutists routinely jump from unpressurized aircraft at altitudes of 10,000 to 13,000 ft AMSL. The risk of hypoxic incapacitation at these altitudes is low, and this risk is further mitigated by the relatively brief durations of exposure to altitudes above 10,000 ft AMSL. Recreational parachutists also jump from altitudes in the 12,000 to

FIGURE 27-8 Ram-air parachute canopies. **A:** A modern *square* ram-air parachute being maneuvered in for a landing. This type of canopy typically has a glide ratio in the range 4–6:1. **B:** Another ram-air parachute canopy during landing. This landing has been achieved with minimal forward speed. Photographs courtesy of Igor Jeremic.

15,000 ft AMSL range where the risk of hypoxic impairment is slightly increased. Often in-aircraft supplemental oxygen, administered through nasal cannulas and/or simple face mask is used to maintain near-normal tissue oxygenation up until a short time before jump execution. Once supplemental oxygen is discontinued, the risk of hypoxic impairment is mitigated by the relatively brief duration of exposure to altitude.

Tandem parachutists, and recreational parachutists attempting free fall formation jumps, often jump from altitudes between 15,000 and 20,000 ft AMSL. At these altitudes, the risk of hypoxic impairment increases, especially when coupled with increased physical workload, with in-aircraft supplemental oxygen becoming essential. A decision concerning the use of oxygen during the descent will depend on the regulations that apply to the activity as well as an analysis of the altitude-time profile of the jump. For example, a risk management assessment for a BASE jump from 20,000 ft AMSL may weigh the altitude acclimatization of the jumpers (having climbed the peak), and the fact that most of the descent phase is undertaken in free fall and will last less than 3 minutes, to reach a decision that such a jump could be safely achieved with the jumpers preoxygenating immediately before the jump and not using supplemental oxygen during the descent. The authors are unaware of any country having national regulations that govern the use of oxygen by BASE jumping parachutists.

Parachuting activities from above 20,000 ft, including military high-altitude parachuting operations, almost always utilize oxygen during the descent phase of the operation. Depending on the jump altitude and descent profile the oxygen may be delivered as follows:

- Continuous-flow supplemental oxygen through nasal cannulas or a loose-fitting face mask before jump execution
- Regulated air-oxygen mix through a sealed face mask
- Positive-pressure oxygen through a sealed face mask

Decompression Illness

Parachuting decompression illness is unusual and most commonly occurs when parachuting activities follow subaquatic activities involving breathing air and/or mixed gases through a self-contained breathing apparatus. Decompression illness can also occur when parachuting is undertaken from high or extreme altitudes, such as military high-altitude parachuting operations. Some additional features of military high-altitude parachuting operations, such as physical exertion, cold exposure, and possible prior subaquatic exposure, may further predispose participants to decompression illness.

There are no published guidelines concerning the safe interval between subaquatic diving and parachuting. General principles (see Chapter 3) indicate that deeper or decompression diving represents a higher risk than shallower nondecompression diving and that higher-altitude parachuting operations represent a greater risk. Taking these factors into consideration it may be reasonable to suggest, for example, that no high-altitude parachute operations be undertaken within 24 hours of a shallow (no greater than 10 m depth in salt or freshwater) dive or within 48 hours of a deeper dive ($\geq$10 m depth in fresh or saltwater). Similarly, a period of 12 and 24 hours might be similarly applied to civilian recreational parachuting after subaquatic diving.

Barotrauma

Parachutists experience pressure changes during both ascent and descent, with the rapidly increasing ambient pressure experienced during free fall usually being of greater significance. Tropospheric free fall at terminal velocity results in a descent rate of approximately 10,000 ft/min. As a result, tympanic membrane barotrauma could be expected as a relatively common, although relatively minor, complication of parachuting. Although anecdotal evidence supports this there is usually no mention of barotrauma in parachuting injury surveys (60–65) possibly because of the relatively minor nature of the injury. Sinus, dental, and other barotrauma injuries are also possible complications of parachuting.

Cold Exposure

Parachuting exposes participants to reduced ambient temperatures coupled with significant further effective temperature reductions due to the windchill effects of free fall and under-canopy motion. Although the adverse effects of cold exposure are not common for recreational parachutists, cold exposure is a serious concern for military high-altitude parachutists who may spend prolonged periods, under canopy or during free fall, exposed to very low temperatures. Record-attempt BASE jumpers, and paragliders operating from alpine launch locations, may also be exposed to significant cold before and after their launch. In these circumstances, the wearing of warm layered clothing and the protection of skin from exposure to windchill become important considerations.

Radiation Exposure

Parachuting from stratospheric altitudes exposes participants to an increased dose of cosmic and solar radiation commensurate with the altitude-time profile of the operation and the protective equipment and clothing utilized.

Opening Shock

Opening shock is the deceleration that results from the deployment of the parachute canopy as the velocity of the parachutist transitions from free fall to under-canopy levels. The effects of parachuting opening shock are influenced by the duration of the deceleration, the magnitude of the deceleration, and the position and equipment of the decelerating parachutist.

Opening shock is increased when the parachute canopy is deployed at higher altitudes. This is because the free fall (terminal) velocity is greater at higher altitude (because of the reduced air density) and therefore the velocity change, between free fall and under-canopy configurations, is greater. Higher altitude also leads to more rapid deployment of the parachute canopy, which also serves to increase the magnitude of the opening shock and reduce the time over which the opening shock occurs.

Typically, a civilian sport parachutist might be exposed to 3 to 5 G opening shock whereas a military high-altitude parachutist might be exposed to an opening shock of up to 10 to 15 G, transmitted to the parachutist's body through the risers. In a recent study of civilian sports, parachuting "hard opening" and "unintentional main opening" accounted for 13 of the 257 injury incidents recorded from 539,885 jumps (63).

The magnitude of opening shock is reduced by lower altitude deployment of a parachute canopy and by design features of the canopy (such as canopy and suspension line materials and construction) that partially absorb the shock of and/or prolong the deployment of the main canopy, thereby spreading the deceleration over a greater period and so reducing the force of the opening shock. Regardless of magnitude, opening shock can result in significant musculoskeletal and soft tissue injury. Such injuries are usually a combination of flail, torsion, or whiplash forces as well as contusions and/or lacerations from the harness or other equipment (60–66).

The risk of injury due to parachute opening shock can be reduced in the following ways:

- Reducing the velocity change by deploying the canopy at a lower yet safe altitude
- Increasing the time over which the velocity changes through equipment design and deploying at a lower altitude
- Adopting a stable and appropriate free fall attitude to reduce flail or twisting as the canopy deploys

Centripetal Effects of Spinning during Free Fall

A parachutist can spin, deliberately and/or inadvertently, during free fall. A spin during free fall may lead to disorientation of the parachutist, but is unlikely to result in any direct physical injury. During testing before Kittinger's 1960 jump from 102,800 ft (31,300 m) free fall dummies entered horizontal spins with rotation rates at or in excess of 200 revolutions (state human limits for rotation and loss of consciousness etc.) per minute (56). A spin during stratospheric free fall (from 26,000 to 58,000 ft to ~58,000 ft . . . depending on latitude), however, has the potential to result not only in severe disorientation but also centripetal effects of reduced limb mobility and blood pooling with associated loss of consciousness. During an earlier jump in the Excelsior series, Kittinger, as a result of a drogue parachute entanglement, lost consciousness in a 120 rpm horizontal spin (56). A small drogue canopy may be used to prevent horizontal spinning during extreme altitude free fall. It is not known how readily a spin can be avoided or aborted during extreme altitude free fall through body posture alone but Andreyev's 1962 jump, from 80,325 ft (24,483 m), was undertaken without the use of a drogue canopy and did not involve horizontal spinning (56).

Midair Collision

Parachutists can collide with each other or with their drop aircraft. Such collisions may occur during any phase of a parachute jump and can result in direct traumatic injury to the parachutist(s) involved; entanglement between the parachutists or the parachutist and aircraft structure; or malfunction of the parachute canopy. A BASE jumper may also collide with the building, structure, or cliff face from which they are jumping. This may occur during free fall or under-canopy flight. The risks associated with parachutist midair collision are mitigated primarily through a combination of training (with formation jumps restricted to more experienced parachutists) and the wearing of protective headgear. In a recent study of civilian parachuting injuries (257 injuries reported from 539,885 jumps), 5 injuries occurred due to collision with the jump aircraft and 4 from collision with another human (63).

BASE jumpers employ a combination of methods to reduce their risk of premature collision with earth-bound structures. Some BASE jumpers use specialized jumpsuits with webbing "wings" between limbs and torso. These suits allow the BASE jumper to fly further away from, for example, a cliff face before deploying their canopy. BASE jumpers may also configure and deploy their canopies with great care to ensure that the initial under-canopy flight is away from the building or cliff face.

Landing Injuries

A parachuting or paraglider landing is the transition from under-canopy flight to terrestrial activities. The landing involves a deceleration from the ground speed during under-canopy flight to being stationary.

The maneuverability of a ram-air canopy allows the parachutist to both steer toward a suitable landing location and to execute a terminal flare that reduces the vertical component of the velocity immediately before contact with the ground. A round parachute, such as may be used in military low-level parachuting, provides less maneuverability for the parachutist and consequently less choice in exact landing locations and less ability to reduce the terminal impact.

A military static-line parachutist (round canopy) might typically land with a vertical speed of 13 mph (21 km/hr or ~9 ft/s or 6 m/s) and a horizontal speed determined primarily by the ground wind speed (67) whereas a military ram-air canopy (e.g., MC-5) would typically operate with a forward speed of 15 to 25 mph (24–40 km/hr) with a vertical speed of 8 to 18 ft/s (2.5–5.5 m/s). Civilian ram-air canopies range from lower performance training parachutes to higher performance parachutes capable of horizontal speeds in excess of 30 mph (50 km/hr) and glide ratios (ratio between horizontal and vertical distance traveled) in the range of 3 to 7. A well-performed ram-air canopy parachuting landing in ideal conditions can be achieved with virtually zero horizontal and zero vertical speed.

Landing injuries are relatively common during parachuting (62,63,65,67–69). Any part of the body may be injured during a parachute landing although lower limb injuries predominate. The risk of a parachuting landing injury will be increased with the following:

- Higher under-canopy ground speeds (e.g., landing downwind, partial canopy malfunction, and small surface area ram-air parachutes designed for speed and agility)
- Reduced control during the landing (e.g., parachutist injury or incapacitation, partial canopy failure)
- Landing in nonideal locations (e.g., uneven or unstable ground, densely wooded areas)
- Inability of parachutist to judge the distance to the ground during the landing (e.g., military night jumps, vision impairment due to dust or foreign bodies)
- Inappropriate delay in deploying the parachute canopy with opening below 1,500 to 2,000 ft AGL (e.g., inexperience, equipment malfunction, human error, fear)
- Use of round, rather than ram-air, parachute canopies

Parachute landing in water also exposes the parachutist to the risk of drowning, especially if injured during the landing or if the parachutist becomes entangled in the parachute equipment while in the water.

Airblast

A parachutist jumping from an aircraft is initially exposed to an airblast (windblast) that is proportional to the airspeed of the aircraft. An extreme example of this may be seen in a pilot ejecting from an aircraft at high speed. Soon after leaving the aircraft, a free fall parachutist experiences the airblast of his/her own airspeed of (usually) 120 mph (190 km/hr).

This airblast can lead to distortion and flapping of external soft tissues, especially of the face. Airblast can also lead to injury of flailing limbs, especially shoulder dislocation. Another common adverse effect of airblast is interference with the parachutist's vision during free fall and under-canopy flight. Airblast interferes with parachutist vision through blepharospasm, excess tearing, and occasionally insertion of an airborne foreign body into the eye.

To protect against airblast effects parachutists wear eye protection, either in the form of goggles or a visor attached to their helmet.

In a study of 539,885 parachuting jumps there were 257 injuries reported, 3 of which were airblast-related shoulder dislocation (63).

Disorientation and Illusions

A parachutist can become disoriented in space and/or time. A variety of factors can result in parachutist disorientation. Tumbling or spinning during free fall, or rapid spiral flight from a malfunctioning partially deployed canopy, can result in SD.

Free fall can be associated with inaccurate time perception, especially for nonexperienced parachutists. This may be due, in part, to the excitement and exhilaration of free fall. Trainee parachutists are drilled to check their altimeter regularly and very frequently during free fall and so avoid the possibility of late canopy deployment resulting from loss of temporal orientation.

Like any other form of flight, parachutists can be subject to visual illusions, especially during the approach and landing. For example, it may be difficult for a descending parachutist to determine whether a plantation pine forest is made up of small or mature trees.

Many parachuting equipment ensembles include a barostatic automatic deployment device (ADD) that is set to deploy the parachute canopy at a predetermined pressure altitude. ADDs are used in both civil and military parachuting, can be set to deploy the canopy at different altitudes, and offer an additional layer of safety in the event of parachutist incapacitation or disorientation.

Medical Fitness for Parachuting

Parasports medical fitness is not covered by the international civil aviation medical standards managed by the International Civil Aviation Organization (ICAO) and contained within Annex 1 to the Chicago Convention (see also Chapter 28). There are no international medical fitness requirements applied to parachuting or other parasports. Not only are there no international medical standards but different nations also manage parasport medical fitness in differing ways. Nations that do ascertain the medical fitness of parasport participants utilize one, or a combination, of the following methods:

- Acceptance of a medical certificate issued by the civil aviation regulatory authority (e.g., FAA, CAA etc.)
- Use of a medical fitness declaration, made by the parasport participant and confirmed or endorsed by a medical practitioner
- Use of a medical fitness declaration made by the parasports participant

The United States, for example, utilizes a combination of the three options outlined in preceding text. In the United States, parachuting aeromedical certification is regulated by the FAA that requires participants to either: (a) hold a valid first, second- or third-class FAA medical certificate; or (b) hold a certificate of physical fitness from a registered physician; or (c) complete a United States Parachute Association–recommended medical statement attesting to the participant's fitness to perform parachuting operations.

In the United Kingdom (UK), a parachutist must declare his or her fitness and obtain medical clearance by completing a "Declaration of Fitness to Parachute/Doctor's Certificate" signed by a medical practitioner. Canada operates a similar system that requires that a parachutist obtain and produce a "medical clearance form" signed, within the previous 24 months, by a medical practitioner. In both the United Kingdom and Canada, the medical declaration/clearance forms contain basic guidance information about medical conditions that may make a candidate unfit for parachuting.

CIVIL UNMANNED AIRCRAFT SYSTEM OPERATIONS

Unmanned Aircraft Systems (UASs) present a unique challenge to the FAA regarding their integration into the National Airspace System (NAS). The UAS consists of three separate but interactive components. The first component of the system is the aircraft itself. Most unmanned aircraft (UAs) carry a payload of some type that is used to accomplish its primary task. This payload is commonly a camera that sends video images to crew on the ground; however, the payload can also be other types of scientific measuring equipment, signal relay equipment, or even cargo. Military systems' payloads include weapons in addition to surveillance equipment. The type and size of possible payloads are limited only by the size of the aircraft and the imagination of system manufacturers.

The second component is the control station, usually called the *ground control station* (GCS). The GCS is the interface that the UA pilot uses to send flight commands to the aircraft and receive information from the aircraft regarding its position, attitude, and status. It is also where the payload operator is located to receive information from the payload and to send commands to the payload. Control stations have as much variety as the aircraft they control. Some of them consist of a single handheld unit, whereas others are large trailers that can hold several people.

The third component is the data link, which is the connection between the aircraft and the GCS. In addition to the signals sent between the GCS and aircraft, this component consists of the antennas and other support equipment that generate and receive those signals. Control and management of the data link is an extra task that is not imposed on pilots of manned aircraft. It is one aspect of these systems that make them unique and that adds to the problems associated with integrating the systems into the NAS.

Because the pilot is separated from the aircraft, information from the aircraft is limited relative to manned aircraft. Data regarding the position, attitude, and status of the aircraft are gained either through direct sensory contact (i.e., seeing and hearing the aircraft) or through the data link. The amount of data that can be transmitted across the data link is necessarily limited because of physical limitations of the system. Therefore, the data that are transmitted regarding aircraft position, attitude and status must be limited to that which is most critical for flight safety and effectiveness.

There are several issues that must be resolved before safe flight in the NAS can become routine. For example, sensing and avoiding aircraft cannot be accomplished in the same manner as manned aircraft. In addition, risk-taking behavior on the part of the pilot might be affected because the pilot does not have a shared fate with the aircraft. However, in this chapter, we will only address a single issue. That issue is the medical implications of integrating UAS into the NAS. These medical implications revolve around two basic questions. The first question is what should be the medical certification requirements for UAS pilots? Should they be the same as for pilots of manned aircraft? This is an important question as far as resolving pilot qualification requirements for these systems. The second question is what kind of injuries and other medical conditions can be expected from the introduction of these systems into the NAS? Even with the pilot removed from the aircraft, injuries and other problems can still be expected. The discussion will include pilots and other personnel as well.

Unmanned Aircraft System Types

Worldwide, there are more than 600 different UASs currently in existence, representing thousands of aircraft. There is a tremendous variety of types of UASs currently in production. Figure 27-9 shows several examples. They range in weight from only a few ounces to more than 25,000 lb. They range in size from models that fit in the palm of your hand to those nearly as large as an airliner. Airframes include fixed-wing, rotary wing, and balloon, with several other variations as well. In addition, there are large differences in the number of engines (and/or motors), performance, and launch and landing methods. Endurance of these aircraft ranges from a few minutes to several weeks.

Criteria for Medical Screening/Selection of Unmanned Aircraft System Pilots

In one sense, the medical criteria for UAS pilots should be no different than for pilots of manned aircraft. The critical issue in both cases is the danger of pilot incapacitation and whether the pilot can perform the required tasks adequately and safety. A panel that was assembled to discuss UAS pilot medical certification concluded that the risk of UA pilot incapacitation was less than for manned aircraft for several reasons (70). First, factors related to changes in air pressure could be ignored, assuming that control stations for nonmilitary operations would be on the ground. Second, many of the current UASs have procedures that have been established for lost data link. Lost data link, where the pilot cannot transmit commands to the aircraft, is functionally equivalent to pilot incapacitation. Third, the level of automation of a system determines the criticality of pilot incapacitation because some highly automated systems (e.g., Global Hawk) will continue normal flight whether a pilot is or is not present. Finally, unlike a manned aircraft, the pilot of an UA can easily be replaced during the flight should they become incapacitated, assuming of course that a qualified pilot is available.

Likewise, the physical demands of piloting an UA are not as great as for manned aircraft because they are not subjected to the same physical stressors as manned aircraft pilots. In addition, many control stations do not require the same level of psychomotor skills or the use of legs and feet in the same manner as manned aircraft cockpits.

Because of the reduced risks of pilot incapacitation and reduced physical demands, it seems reasonable to suggest that medical certification requirements for UA pilots should be less severe than for manned aircraft pilots. In fact, a recent report from Tvaryanas (71) concluded that, at least for pilots of large and weaponized UAS flown by the USAF, the current manned military aircraft medical standards were unnecessarily restrictive. The FAA, on the other hand, has not yet reached this conclusion for nonmilitary pilots, suggesting that current civilian pilot medical standards are adequate for UA pilots and that exceptions can be handled through a waiver process (1).

Most Common Contributing and Causal Factors in Injuries Involving Unmanned Aircraft Operations

Unlike all other types of aircraft, the pilot is usually not in danger when the UA crashes. However, this does not mean that there is no potential for injuries, or even fatalities from UA. This section will review some common contributing and causal factors in injuries involving UA operations, and suggest potential sources and types of injuries that could occur with these operations. Because of the nature of these operations, the data are limited to support some of the

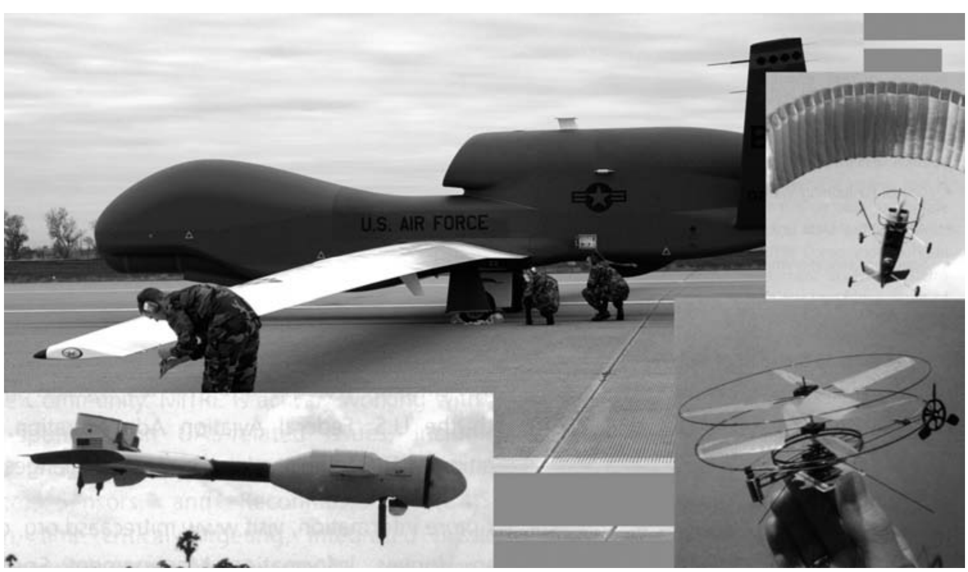


FIGURE 27-9 Examples of the large variety of unmanned aircraft types.

assumptions made in this section. Nevertheless, it is still important to suggest potential injuries so that preventive steps might be taken before a problem arises.

Contact with the Aircraft

An analysis of more than 300 accidents of military UA did not reveal any injuries at all (72). Likewise, a study of 221 accidents of military UA did not report any injuries to crew or civilians (73). However, there are a few scattered reports of injuries and deaths associated with personnel coming into contact (or almost coming into contact) with UA. In a report summarizing accidents of UA flown by the U.S. Army, 2 accidents, out of a total number of 56, reported injuries to personnel (74). In one accident, an aircraft crashed into the metal doors of a building. An individual inside the building was injured in a rush to take cover, but did not come into direct contact with the aircraft. In the second accident, an external pilot was injured when the aircraft's wing struck the flight control box that the pilot was holding, causing minor cuts and lacerations.

From other sources, an accident occurred with a Hunter UA (Figure 27-10) in which the pilot, while landing the aircraft, ran himself over, breaking his leg (Ft. Huachuca UAV Training Center, *personal communication*). In addition, personnel working with the Pioneer UA have reported injuries associated with coming into contact with the propeller (Ft. Huachuca UAV Training Center, *personal communication*).

Propeller-related injuries are the most common type seen in the world of radio-controlled (RC) hobbyist flying, with the vast majority of these being finger injuries (Jay Mealy, Aeronautical Modeling Association, *personal communication*). However, there have been two RC-related deaths since 1995 due to personnel being struck by an aircraft (Jay Mealy, *personal communication*).

October 2006 saw the first known case of someone being killed accidentally by an UA (75). The accident, which occurred on October 3, 2006, in the Democratic Republic of Congo's capital city of Kinshasa, resulted when a B-Hunter UA, flown by the Belgian Army, apparently experienced the failure of both of its engines shortly after takeoff from Kinshasa's N'Dolo airport. Subsequent news reports suggested that the pilot was trying to abort the takeoff and purposely shut off the engines (76). The aircraft crashed on a street approximately 1 km from the airport, killing a woman. This accident came shortly after another B-Hunter was shot down in August 2006 in the same area (77). That crash resulted in injuries to six people.

Workstation-Related Injuries

Because many of the control stations are similar to office workstations, there is a possibility that personnel using those control stations will be susceptible to the same types of injuries that plague office workers. Figure 27-11 shows the control station for a Shadow UA. The control station contains a keyboard, trackball, and joystick for handling user interactions with the aircraft. Although there is currently no information about workstation-related problems, there is an obvious possibility for the development of certain kinds of repetitive motion disorders, sore backs or necks, or other problems associated with office workstations.

In addition to normal office workstation controls, an additional condition for potential problems is the existence of nonstandard controls or the placement of displays that do not conform to human factors standards design principles. For example, Figure 27-12 shows the control station for a Predator UA. Looking at the figure, it is easy to see that the joystick on the right is too large to accommodate the pilot's hand. In addition, what is not seen in this figure is a second large display sitting above the out-the-window display that is shown. Other examples of nonstandard controls can easily be found in many other systems.

FIGURE 27-10 Hunter unmanned aircraft. Courtesy of Northrop Grumman Corporation.

FIGURE 27-11 Shadow control station, showing typical office workstation components.

FIGURE 27-12 Predator control station, showing oversized joystick control on *right*.

System-Specific Injuries

Some injuries are to be expected that will be unique to particular types of systems. Some systems, for example, have rocket-assisted takeoff (RATO) bottles that are used during launches. Other types of launch and recovery equipment could prove dangerous to crewmembers as well. Some aircraft use catapults or slingshots for launching the aircraft. Recovery systems include nets and guy-wires. Figure 27-13 shows a Raven UA that is launched by throwing it. Systems that are launched in this manner range from a few pounds up to more than 10 lb in weight. Although there is currently no data regarding injuries from hand launches, the likelihood for shoulder injuries certainly exists.

Other Potential Problems

In addition to the human factors issues discussed, other potential problems exist that will be dependent on how certain systems are used. For example, some systems, such as Aerovironment Incorporated's Helios UAS, can stay aloft for weeks at a time. Companies employing these aircraft have to deal with potential problems of crew fatigue and crew shifts. Although there is, perhaps, the potential for abuse of crewmembers in regard to the length of a shift, it is more likely that standard shift practices will be adopted either from the military, the government, or industry. However, there is a need for the development of standards and guidelines regarding the length of shifts and procedures for changing crews during a flight.

FIGURE 27-13 Hand-launching a Raven.

Conclusions

The integration of UAS into the NAS presents unique challenges to the FAA. It also presents new opportunities for manufacturers and users. However, with every new opportunity there are also new risks. Some risks, such as being hit by a moving aircraft, are obvious, and there have been documented cases where this has occurred. Other risks are not as apparent and will only manifest themselves over time as the use of these systems increases and spreads to a wider population. At this point in time, the potential for some of these risks is not known for UAS in civilian airspace because there is no data available to indicate the incidence of certain types of injuries or other risks. As with all risks, if the dangers are known, there are training protocols, procedures and design changes that can be implemented to mitigate those risks. Now is the time to begin that task.

REFERENCES

1. Flight Research Group, Advanced Maneuver & Upset Recovery Training. http://www.calspan.com/upset.htm. (Last accessed on December 24, 2007.)
2. Robson D. *Skydancing: aerobatic flight techniques*. Newcastle: Aviation Supplies & Academics, 2000.
3. Williams RS. Adverse effects of Gz in civilian aerobatic pilots. *Aviat Space Environ Med* 1998;69(Suppl 5):55.
4. Muller TU. G-induced vestibular dysfunction ('The Wobblies') among aerobatic pilots: a case report and review. *Ear Nose Throat J* 2002;81(4):269–272.
5. Epley JM. New dimensions of benign paroxysmal positional vertigo. *Otolaryngol Head Neck Surg* 1980;88(5):599–605.
6. Epley JM. The canalith repositioning procedure: for treatment of benign paroxysmal positional vertigo. *Otolaryngol Head Neck Surg* 1992;107(3):399–404.
7. National Transportation Safety Board. www.ntsb.gov/ntsb/query .asp. (Last accessed on December 24, 2007.)
8. Martin TE. The Ramstein airshow disaster. *J R Army Med Corps* 1990;136(1):19–26.
9. Kamel F, Engel LS, Gladen BC, et al. Neurologic symptoms in licensed private pesticide applicators in the agricultural health study. *Environ Health Perspect* 2005;113:877–882.
10. National Transportation Safety Board Report. *ARG-06-02, Annual review of aircraft accident data: U.S. General aviation, calendar year 2002*. 2006.
11. Federal Aviation Administration. *Lighter-than-air operations*. eBALLOON.ORG, http://www.faa.gov/other_visit/aviation_industry/designees_delegations/designee_types/ame/media/Section%20II.4.5%20Lighter-Than-Air%20Operations .doc. (Last accessed on Aug. 30, 2007.)
12. *The history of hot air ballooning*. Wikipedia The Free Encyclopedia, http://www.eballoon.org. (Last accessed on December 24, 2007.)
13. Airship Association. *Frequently asked questions about airships*. http://www.airship-association.org/whatis.html. (Last accessed on Aug. 30, 2007.)

14. *Hot air balloon*. Wikipedia The Free Encyclopedia, http://www.en.wikipedia.org/wiki/Hot_air_balloon. (Last accessed on December 24, 2007.)
15. *First successful solo attempt*. eBALLOON.ORG, http://www.eballoon.org/flights/first-around-the-world-solo.html. (Last accessed on December 24, 2007.)
16. De Voogt AJ, Van Doorn RR. Balloon crash damage and injuries:an analysis of 86 accidents, 2000–2004. *Aviat Space Environ Med* 2006; 77:556–558.
17. Hasham S, Majumder S, Southern SJ, et al. Hot-air ballooning injuries in the United Kingdom (January 1976–January 2004). *Burns* 2004;30(8):856–860.
18. National Transportation Safety Board. *Aviation accident database and synopses*. www.ntsb.gov/aviation/aviation.htm. (Last accessed on Aug. 30 2007.)
19. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 103: Ultralight Vehicles, Subpart 103.1: Applicability, Department of Transportation*, 2007.
20. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 103: Ultralight Vehicles, Subpart 103.7: Certification and Registration, Department of Transportation*, 2007.
21. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 61: Certification: Pilots, Flight Instructors, and Ground Instructors, Subpart 61.53: Prohibition on Operations During Medical Deficiency, Department of Transportation*, 2007.
22. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 61: Certification: Pilots, Flight Instructors, and Ground Instructors, Subpart 61.23: Medical Certificates-Requirements and Duration, Department of Transportation*, 2007.
23. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 103: Ultralight Vehicles, Subpart 103.11: Daylight Operations, Department of Transportation*, 2007.
24. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 103: Ultralight Vehicles, Subpart 103.15: Operations Over Congested Areas, Department of Transportation*, 2007.
25. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 103: Ultralight Vehicles, Subpart B-Operating Rules, Department of Transportation*, 2007.
26. BRS Ballistic Recovery Systems. *BRS Ballistic parachutes:information for emergency personnel*. http:brsparachutes.com/ViewDocument.aspx?DocumentID=34. (Last accessed on December 24, 2007.) 2006.
27. NTS Board. Chapter 168: Investigate an accident. In: *General aviation operations inspector's handbook, order 8700.1*. National Transportation Safety Board, 2006.
28. Pagan BJ, de Voogt AJ, Van Doorn RRA. Ultralight aviation accident factors and latent failures: a 66-case study. *Aviat Space Environ Med* 2006;77:950–952.
29. Schulze WW. Injury prophylaxis in paragliding. *Br J Sports Med* 2002;36(5):365–369.
30. Gauler R, Moulin P, Koch Hans, G, et al. Paragliding accidents with spinal cord injury: 10 years' experience at a single institution. *Spine* 2006;31(10):1125–1130.
31. Schulze W. Pattern of injuries and prophylaxis in paragliding. *Sportverletz Sportschaden* 2000;14(2):41–49.
32. Fasching G, Schippinger G, Pretscher R. Paragliding accidents in remote areas. *Wilderness Environ Med* 1997;8(3):129–133.
33. FAA Aerospace Medical Certification Division. *Pilot medical certification statistics report*. Civil Aerospace Medical Institute, 2007.
34. Bohnsack M, Schroumlter E. Injury patterns and typical stress situations in paragliding. *Orthopade* 2005;34(5):411–418.
35. Exadaktylos AK, Sclabas G, Eggli S, et al. Paragliding accidents—the spine is at risk. A study from a Swiss trauma centre. *Eur J Emerg Med* 2003;10(1):27–29.
36. Kruumlger-Franke M, Siebert CH, Pfoumlrringer W. Paragliding injuries. *Br J Sports Med* 1991;25(2):98–101.
37. Federal Register, Department of Transportation, Federal Aviation Administration. *14 CFR Parts 1, 21* et al. *Certification of aircraft and airmen for the operation of light sport aircraft*. Final Rule. July 24, 2004.
38. Aircraft Owners and Pilots Association. Website:http://www.aopa.org/sportpilot/. (Last accessed on Aug. 30 2007.)
39. Experimental Aircraft Association. Website:http://www.sportpilot.org/. (Last accessed on August 30 2007.)
40. Gleim IN, Gleim GW. *Sport pilot syllabus*. Gainesville: Gleim Publications, 2006.
41. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 61: Certification: Pilots, Flight Instructors, and Ground Instructors, Subpart 61.53: Prohibition on Operations During Medical Deficiency. Department of Transportation*, 2007.
42. U.S. Code of Federal Regulations (CFR), *Title 14: Aeronautics and Space, Part 61: Certification: Pilots, Flight Instructors, and Ground Instructors, Subpart 61.303: If I want to operate a light-sport aircraft, what operating limits and endorsement requirements in this subpart must I comply with?, Department of Transportation*, 2007.
43. Aircraft Owners and Pilots Association. *The 2005 nall report*. http//:www.aopa.org/asf/publications/05nall.pdf. (Last accessed on December 24, 2007.)
44. U.S. Army Field Manual FM-3-04.203 (Fundamentals of Flight), Incorporated into FM-3-04.201, March 10, 1988.
45. *Non-auditory effects of noise exposure*. www-nehc.med.navy.mil/downloads/occmed/hctoolbox/Toolbox_files/Non_Auditory_Effects_of_Noise.ppt#290,16,Cognition. (Last accessed on August 30, 2007.)
46. O'Hare D, Chalmers D, Scuffham P. Case-control study of risk factors for fatal and non-fatal injury in crashes of rotary-wing aircraft. *J Safety Res* 2006;37:293–298.
47. Baker SP, Grabowski JG, Dodd RS, et al. EMS helicopter crashes: what influences fatal outcome? *Ann Emerg Med* 2006;47(4):357–360.
48. Thies KC, Sep D, Dersken R. How safe are HEMS-programmes in Germany? a retrospective analysis. *Resuscitation* 2006;68(3):359–363.
49. Holland J, Cooksley DG. Safety of helicopter aeromedical transport in Australia: a retrospective study. *Med J Aust* 2005;182(1): 17–19.
50. Hayden MS, Shanahan DF, Chen LF, et al. Crash-resistant fuel system effectiveness in civil helicopter crashes. *Aviat Space Environ Med* 2005;76(8):782–785.
51. Myer J. *An introduction to deployable recovery systems (SAND85-1180*. Sandia National Laboratories, 1985.
52. Barnhart. RK. In: Steinmetz S, ed. *The Barnhardt dictionary of etymology*, 2nd ed. Bronx: H.W. Wilson Co., 1988.
53. *FAI sporting code*. Lausanne: Fédération Aéronautique Internationale, 2006.
54. *Fantastic catch in the sky, record leap toward earth: space race soars with a vengeance*, in LIFE magazine. 1960 (29 August). 20–25.
55. Aviation, stunt flyer Cliff Winters, in LIFE magazine. 1961 (17 November).
56. Ryan C. *The pre-astronauts:manned ballooning on the threshold of space*. Annapolis: Naval Institute Press, 1995.
57. Kittinger JW, Wentzel V. *The long, lonely leap*. *Natl Geogr Mag* 1960;118(6):854–873.
58. Offman C. Terminal velocity: what it's like to free-fall 130,000 feet, in WIRED magazine. 2001 (August). p. 128–135.
59. Vivian EC. *A history of aeronautics*. New York: Harcourt, Brace & Company, 1921.
60. Bricknell MC, Craig SC. Military parachuting injuries: a literature review. *Occup Med (Lond)* 1999;49(1):17–26.
61. Baiju DS, James LA. Parachuting: a sport of chance and expense. *Injury* 2003;34(3):215–217.
62. Ekeland A. Injuries in military parachuting:a prospective study of 4499 jumps. *Injury* 1997;28(3):219–222.

63. Westman A, Bjornstig U. Injuries in Swedish skydiving. *Br J Sports Med* 2007;41:356–364.
64. Barrows TH, Mills TJ, Kassing SD. The epidemiology of skydiving injuries: world freefall convention, 2000–2001. *J Emerg Med* 2005;28(1):63–68.
65. Ellitsgaard N. Parachuting injuries: a study of 110,000 sports jump. *Br J Sports Med* 1987;21(1):13–17.
66. Marriott M, Macdonell R, McCrory P. Flail arms in a parachutist: an unusual presentation of hereditary neuropathy with liability to pressure palsies. *Br J Sports Med* 2002;36(6):465–466.
67. Knapik JJ, Craig SC, Haunet KG, et al. Risk factors for injuries during military parachuting. *Aviat Space Environ Med* 2003;74(7):768–774
68. Westman A, Bjornstig U. Fatalities in Swedish skydiving. *Accid Anal Prev* 2005;37(6):1040–1048.
69. Dawson M, Asghar M, Pryke S, et al. Civilian parachute injuries; 10 years on and no lessons learned. *Injury* 1998;29(8):573–575.
70. Williams KW. *Unmanned aircraft pilot medical certification requirements*. Technical Report No. DOT/FAA/AM-07/3. Washington, DC: U.S. Department of Transportation, Federal Aviation Administration, Office of Aerospace Medicine, 2007.
71. Tvaryanas, AP. *The development of empirically-based medical standards for large and weaponized unmanned aircraft system pilots. Document # HSW-PE-BR-TR-2006-0004*, U.S. Air Force, 311th Performance Enhancement Directorate, Performance Enhancement Research Division, 2006.
72. Williams KW. *A summary of unmanned aircraft accident/incident data:Human factors implications. Technical Report No. DOT/FAA/AM-04/24*. Washington, DC: U.S. Department of Transportation, Federal Aviation Administration, Office of Aerospace Medicine, 2004.
73. Thompson, WT, Tvaryanas, AP, Constable, SH. *U.S. military unmanned aerial vehicle mishaps:assessment of the role of human factors using Human Factors Analysis and Classification System (HFACS). Document # HSW-PE-BR-TR-2005-0001*. U.S. Air Force, 311th Performance Enhancement Directorate, Performance Enhancement Research Division, 2005.
74. Manning, SD, Rash, CE, LeDuc, PA, et al. *The role of human causal factors in U.S. Army unmanned aerial vehicle accidents. Report # 2004-11*. U.S. Army Aeromedical Research Laboratory, 2004.
75. La Franchi, P. *EUFOR details Belgian B-Hunter UAV crash that caused civilian death*, 2006. http//:www.flightglobal.com/Articles/Article.aspx?liArticleID=209716&PrinterFriendly=true (Last accessed on Aug. 30, 2007).
76. Belgian Aviation History Association (BAHA, 2006). *EUFOR details Belgian B-Hunter UAV crash*. www.brakke.be/forum/viewtopic.php?p=1268&sid=84081ebd354ab27da480d06368dea179. (Last accessed on Aug 30 2007.)
77. FlightGlobal.com. *Belgium resumes Congo UAV operations after B-Hunter is shot down*. 2006.www.flightglobal.com/articles/2006/08/14/208465/belgium-resumes-congo-uav-operations-after-b-hunter-is-shot.html. (Last accessed on August 30 2007.)

CHAPTER 28

The Practice of International Aerospace Medicine

Claude Thibeault

> So, may it be; let us hope that the advent of a successful flying machine, now only dimly foreseen and nevertheless thought possible, will bring nothing but good into the world; that it shall abridge distance, make all parts of the globe accessible, bring men into closer relation with each other, advance civilization, and hasten the promised era in which there shall be nothing but peace and goodwill among men.
>
> —*Octave Chanute, 1894*

The practice of aviation medicine has followed the evolution of aviation over the years. From the birth of aviation, a medical component was first added to military operations, followed by a commercial component and finally a space component. Eventually aerospace medicine was accepted to represent all practitioners in this field whether their activities included the space component or not. Because of the international nature of the subject, the aerospace medicine practitioner, also often referred to as an *aviation medical examiner* (AME) (civilian) or *flight surgeon* (military, space agencies), has many interactions in the international arena. However, there has never been a formally recognised "International Aerospace Medicine Specialist" *per se* or, probably, will there ever be. It is more appropriate to indicate that a number of aerospace medicine practitioners have an impact in the international arena by virtue of their positions in influential international organizations. However, there is little doubt that these aerospace medicine practitioners work in a unique practice environment.

The other important aspect that has particularly affected this practice environment is the evolution of aerospace medicine itself. Although the initial and only objective of the early flight surgeon was to support the flyers (pilots), that objective has been expanded significantly over the years and particularly since the last publication of this textbook.

The aim of this chapter is to briefly describe the evolution of some of the international organizations involved in aviation and how that evolution has impacted on the aerospace medicine practice of medical practitioners that belong to or work for those organizations. When appropriate, some detailed activities of these organizations will be described. Although the World Health Organization (WHO) is not directly involved in aviation, it will take an important place in this chapter and its regulations will be reviewed because public health can have a major impact on aviation operations.

INTERNATIONAL CIVIL AVIATION ORGANIZATION

Parallel to the development of aviation, it is in general and commercial aviation that we see the first attempt at international medical cooperation. From a medical practitioner standpoint, it all started with the International Commission for Air Navigation (ICAN), the predecessor of the International Civil Aviation Organization (ICAO).

Pre-1944

The first successful manned balloon crossing of the English Channel was accomplished by an Englishman in 1785 and began to set the stage for early territorial concerns about aerial navigation. However, the first recorded international powered flight, made by Louis Blériot across the English

Channel in his 25 horsepower monoplane in 1909, certainly hastened the need for international air navigation agreements between nations. In 1910, the French government invited 21 European states to meet in Paris to address air navigation issues within Europe. The conference met for 6 weeks but other fundamental navigational issues took precedence over the development of international medical standards during these sessions.

The outbreak of World War I in 1914 accelerated the national military requirements for aviation medical standards, and temporarily eliminated the possibility of international cooperation. However, by the end of the war in 1918, as aviation activities were increasing rapidly in many countries, nations again recognized the need for international cooperation in matters of air navigation. The French government organized the Paris Peace Conference during the period 1919 to 1920, in which 32 allied and associated states met to draw up a peace agreement. Out of this came several treaty pacts with various nations, incorporating the Constitution of the international organization, which became known as the *League of Nations*. During these proceedings, on October 13, 1919, the Aeronautical Commission was formed, with members from Belgium, Bolivia, Brazil, the British Empire, Cuba, France, Greece, Italy, Japan, Portugal, Romania, the Kingdom of the Serbs, Croats and Slovenes, Siam, and the United States, and the resulting International Air Convention was eventually ratified by 38 states. This led to the formation of the permanent ICAN within the League of Nations. During the first session of the ICAN, held in Paris during July 11 to 28, 1922, a Medical Subcommission (comprising Colonel Heald, British Empire, and Dr. Garseau, France) was formed to deal with "Settlement of the rules of Annex E, as provided for in Article 13 of the Convention, of the medical examination and the minimum standard of requirements" (1). The Medical Subcommission's work was deferred to the second session of the ICAN, which took place during October 25 to 27, 1922, in London, the United Kingdom, when the medical resolution, No. 35, was adopted, outlining requirements of mental and physical fitness for "a pilot, navigator, engineer, or member of the operating crew of aircraft engaged in public transport" (2).

The ICAN Secretariat was located in Paris, while meetings were rotated through Brussels, London, Paris, and Rome. Between 1922 and 1926, ICAN organized regular meetings, revised and updated annexes to the Convention, and distributed and coordinated air navigation information to the contracting states. However, weighted voting given to alliances formed during World War I created differences among participating states, and in spite of amendments to rectify the inequalities, the much-needed unity began to weaken (3). Although by 1933 there were 53 member states within the League of Nations, maintaining and attracting other members became increasingly difficult. Although U.S. President Woodrow Wilson himself strongly supported the League of Nations, the U.S. Senate did not, and the United States did not ratify the Paris Convention, in spite of early active participation. Further, Russia and Germany did not participate in the Paris Convention. Germany later joined the League of Nations, in 1926, but withdrew membership, along with Japan in 1933, whereas Russia did not join until 1934. Spain, unhappy with the inequality of contracting states in ICAN, held its own Ibero-American Air Convention in Madrid in 1926, inviting the Latin American and Caribbean countries, and Portugal (3). Therefore, by the early 1930s ICAN was losing its effectiveness in maintaining a spirit of international cooperation concerning air navigational matters. The hostilities that developed between nations resulting in World War II thwarted further activities of ICAN, and the office was eventually closed when Paris was invaded in 1940.

Chicago Convention (1944)

Between, during, and immediately after both World Wars, aviation experienced remarkable growth and technologic advancement, requiring nations to develop their own medical standards to reduce aviation casualties resulting from medical inaptitude or incapacitation. After World War I, utilizing military aviation medical standards as a foundation, civilian medical standards for aviation personnel made their first appearance in several countries, such as the United States, the United Kingdom, France, and Germany. By the end of World War II, larger aircraft were capable of carrying passengers and cargo internationally over long distances and the need for coordinated international air navigation agreements between nations became urgent. Therefore, the U.S. government began to study postwar aviation problems in 1943, and after initial discussions with several countries realized that aviation issues could be solved only with international cooperation. President Franklin D. Roosevelt authorized invitations to 55 countries to attend an international conference in November 1944 on civil aviation matters in Chicago, and the resulting "Convention on International Civil Aviation" came to be known as the *Chicago Convention*. In spite of immediate postwar political differences, 52 to 55 invited foreign states attended and worked tirelessly, especially in the technical field, to set down rules and regulations, known as *Standards*, regarding air navigation, to be applied uniformly and internationally in all states that signed the Convention. At the conclusion of the 37-day conference, 32 states signed the Convention, agreeing to establish the ICAO. This organization would not, however, become official until 26 states had *ratified* the Convention. To allow other participating states time for this, the conference had signed an Interim Agreement, which allowed for the creation of the "Provisional International Civil Aviation Organization" (PICAO), which operated from August 1945 to April 1947. On April 4, 1947, after the 26 states signed the Convention, ICAO became a reality, and Montreal, Canada was chosen as its headquarters, where it is to be found today. As ICAO became firmly established, the ICAN member states agreed to dissolve ICAN, and the former General Secretary of ICAN, Dr. Albert Roper, from France, was elected the first Secretary General of ICAO. To further enhance the international spirit of cooperation, ICAO became a specialized agency of the United Nations (UN), which had been established in October 1945.

Currently, in 2007, there are 189 contracting states of ICAO, continually working toward harmony in global air navigation issues, making ICAO one of the major UN agencies. ICAO's structure has a sovereign body, the Assembly, comprising representatives from all contracting states, and a governing body, the Council, which consists of 36 states elected by the Assembly for a 3-year term. The chief officers of ICAO are the President of the Council and the Secretary General, the latter having responsibility for the several hundred international civil servants working permanently at ICAO, known as *the Secretariat*. The Assembly meets at least once in 3 years at its headquarters in Montreal. To facilitate its activities worldwide, ICAO has divided the world into seven regions, with offices located in Bangkok, Cairo, Dakar, Lima, Mexico City, Nairobi, and Paris.

One of the primary tasks of ICAO is to continually review and revise the "Standards and Recommended Practices" (SARPs) contained in the 18 Annexes to the Chicago Convention of 1944. For safety or regularity of international air navigation, the Standards are mandatory for the member states, although a state may decide to file a difference (notifying ICAO that it will not implement the standard in question) because it may not be possible to implement a particular standard in that state's current environment. A recommended practice is not mandatory but is "desirable" in the interest of safety, regularity, or efficiency of international air navigation.

In January 1999, ICAO launched its "Universal Safety Oversight Audit Programme" (USOAP), a precedent-setting task, with the goal of auditing all contracting states to ensure the uniform application of SARPs, to be completed by 2001 (4). Since then, audit of states against ICAO SARPs has become a vital part of ICAO's activities. In 2008, ICAO intends to publish the results of such audits, although many states already do this, on a voluntary basis.

Within the permanent Secretariat of ICAO, and located in the Air Navigation Bureau, headed by an aerospace medicine specialist, is the Aerospace Medicine Section, where the relevant health and safety issues relating to the human element associated with aviation are researched, studied, and debated internationally. When agreement has been reached, new medical SARPs are published, or existing ones are updated. Until recently, these health and safety issues were largely limited to pilots, engineers, navigators, and air traffic controllers. Indeed, one of the section's primary responsibilities was, and remains, the continual reviewing and updating of the medical aspects of Annex 1 to the Chicago Convention (Personnel Licensing), Chapter 6, which contains the medical licensing requirements for aviation personnel, and reviewing and revising the "*Manual of Civil Aerospace Medicine*" (5) that provides supporting guidance material.

In the last 3 years, two important events modified the approach of ICAO and its Aerospace Medicine Section. First of all, in 2004, ICAO initiated an extensive review of the medical aspects of Annex 1 of the Convention, which had no major review for many years. The review itself is not a significant event because it is a primary function of the organization as mentioned earlier. However, the approach and the recommendations will change ICAO's future functioning. Instead of limiting itself to its own Aerospace Medicine Section, ICAO created a working group of aerospace medicine specialists from several member states and from several international aviation organizations. In the last decade or so, the model had been used on a small scale before and had generated a useful publication, the "*Manual on Prevention of Problematic Use of Substances in the Aviation Workplace*" (6). After approving the recommended major changes to the Annex, the ICAO Council advised that the working group should meet more frequently to keep pace with the rapid evolution of scientific data and avoid the need for infrequent, and therefore major, revisions in the future.

The other significant event also took place in 2004. Prompted by the recommendations of the Air Passenger Health Issues Working Group of the European Civil Aviation Conference (ECAC), the ICAO Assembly decided to include passenger health in its definition of safety. In October 2004, the Assembly declared "that the protection of the health of passengers and crew on international flights is an integral element of safe air travel and that conditions should be in place to ensure its preservation in a timely and cost-effective manner." The Assembly requested the Council to:

- "review existing SARPs related to passenger and crew health and develop new SARPs where appropriate with due consideration of global health issues and recent developments in air transport operations
- establish suitable institutional arrangements to coordinate efforts by contracting states and other members of the international civil aviation community aimed at protecting the health of passengers and crew
- develop Standards and Recommended Practices in the appropriate Annexes of the Convention in order to address contingency plans to prevent the spread of communicable diseases by air transport
- support further research on the consequence of air transport on the health of passengers and crews
- report on the implementation of this resolution in all aspects to the next ordinary Session of the Assembly" (7)

In 2005, ICAO established an international working group to address the immediate threat of a human influenza pandemic to the aviation industry, its workers, and the traveling public. At the time, ICAO member states were requesting advice from ICAO regarding planning for such an event and it was apparent that ICAO was best placed to coordinate the aviation response. The working group was formed from representatives of the WHO, with technical assistance from the U.S. Centers for Disease Control and Prevention (CDC), a representative of Airport Council International (ACI) and one from the International Air Transport Association (IATA), together with other representatives from several ICAO member states, particularly from Asia, as that region had been most affected by the outbreak of severe acute respiratory syndrome (SARS) in 2003 (and therefore had experience of the need for pandemic planning) and was most at risk from an outbreak of human pandemic influenza.

Two aerospace medicine specialists and another physician with extensive aviation industry knowledge were among the representatives.

The outcome of the working group was the publication of "Guidelines for States Concerning the Management of Communicable Disease Posing a Serious Public Health Risk" (8). These guidelines include sections on general preparedness, airport preparedness, and airline preparedness.

As the activity given in the preceding text was going on, ICAO was also involved in the WHO "Informal Working Group for the Implementation of the International Health Regulations (IHR) (2005)". As this subject will be discussed in further detail in the subsequent text, suffice to say that the participation of ICAO in this endeavor facilitated the first task of the working group, which was to comment on the proposed update of the IHR, and was particularly significant in the second task, which was to develop guidelines to assist states to implement the IHR in the different modes of transportation.

Because the IHR refers to the ICAO document "Aircraft General Declaration: Health Part," ICAO's Chief of the Aerospace Medicine Section initiated, in cooperation with the ICAO Facilitation Section, a review of Annex 9 to the Chicago Convention, in which the Aircraft General Declaration can be found. This review was carried out with unusual rapidity. The major new positions and/or changes to Annex 9 are the following:

- a new Standard for member States to establish a national aviation preparedness plan
- requirement for first aid provision at airports upgraded from a Recommended Practice (desirable) to a Standard (mandatory)
- pilot in command (PIC) to inform air traffic control of suspected communicable disease on board (previously to "notify health authorities" without specifying the mechanism, which has been found by experience to be unreliable)
- revised list of signs and symptoms indicative of a communicable disease on health part of aircraft general declaration
- recommendation to use the new Passenger Locator Card (PLC) for improved passenger contact tracing in the event of a suspected contact with a sick traveler

As follow-on to the ICAO communicable disease planning guidelines, and to facilitate a harmonized response by the aviation sector to any pandemic, ICAO, assisted by international experts in aerospace medicine, developed project CAPSCA (Co-operative Arrangement for the Prevention of Spread of Communicable Diseases through Air Travel). This project is centered in Asia and aims to reduce the risk of spreading influenza having pandemic potential, and similar communicable diseases, by air travellers through cooperative arrangements between participating states/administration and airports. As part of the project, an ICAO expert qualified in aerospace medicine and provided for the project will visit the participating airports to assist the concerned authorities in implementing the guidelines. Another important goal of the project is to establish an expert group (Regional Aviation Medicine Team) that can provide ongoing guidance to all states/administrations in the region. The first training workshop took place in Singapore in late 2006 and there were 25 participants from the following organizations and states/administrations: ICAO, WHO, CDC, ECAC, IATA, ACI, the United States, Hong Kong, Macao, Thailand, Malaysia, Philippines, Republic of Korea, New Zealand, and Singapore. As the project was successfull in Asia, a similar one was started in Africa with an aerospace medicine seminar held in Libreville, Gabon. It was followed in March 2008 by two workshops, one in Dakar, Senegal and one in Nairobi, Kenya. At these workshops, two Regional Aviation Medicine Teams were formed.

The role of the ICAO Aerospace Medicine Section also involves monitoring recent developments in aerospace medicine internationally, to provide guidance to licensing authorities on all operational aeromedical issues with emphasis on aeromedical training and the dissemination of information through worldwide ICAO regional civil aerospace medicine seminars, and by holding ICAO update sessions in conjunction with international aerospace medicine congresses and scientific meetings.

The description given in the preceding text gives a clear example of the practice of aerospace medicine in an international setting, a unique practice environment. A few other examples will be described later.

WORLD HEALTH ORGANIZATION

At present, there is no aerospace medicine specialist working for the WHO. However, as mentioned in the introduction and as was seen in the previous section, the WHO can have a major impact on the aviation industry through a number of its activities. It is therefore important to briefly describe those activities and recognize the interfaces between the WHO and the other international bodies involved in aviation, and where the aerospace medicine specialist may be involved.

Since its founding in 1948, the WHO has led the world alliance for "Health for All." It is the specialized public health agency of the UN, with 193 member states, promoting technical cooperation to promote health among nations.

The WHO has four main functions, which include the following:

- To give worldwide guidance in the field of health
- To set global standards for health
- To cooperate with governments in strengthening national health programmes
- To develop and transfer appropriate health technology, information and standards

The following subsections represent the activities relevant to aerospace medicine within these functions.

International Health Regulations

1. Introduction

   Most of the diseases with the potential to be transmitted during travel can also be transmitted at the destination. Some diseases may incubate during a flight or series of flights and eventually be transmitted at the destination.

In other cases, the cargo may cause health risks at the destination. Regulations and procedures (quarantine, WHO IHR, disinsection, etc.) have therefore been put in place to prevent disease outbreaks. Although not 100% effective, these measures, along with an increasing general awareness of risk from communicable disease, have probably contributed to the prevention of catastrophic outbreaks in recent decades.

2. Quarantine
It seems the original idea for quarantine was first implemented around 630 AD when Gallus established the concept of a sanitary zone in the diocese of Cahors, France. Armed guards were placed at all points of entry to prohibit movement. A few centuries later, the Knight Hospitallers of the Order of St. John of Jerusalem were the first to adopt the 40-day quarantine because it was the amount of time Christ spent in the wilderness. In Venice, Italy, in 1348 AD, incoming vessels, crew, and passengers were detained for 40 days primarily to guard against plague. The idea caught on throughout Europe in the 16th and 17th centuries, and the word "quarantine" entered the English vocabulary from the Italian word *quaranta* which means 40.

Quarantine is effective as long as the quarantine period exceeds the incubation period. Major outbreaks of cholera followed the rapid increase in travel brought about by the new technologies of steamships and railroads and the forerunners to our major international health organizations were brought about by the need of governments to cooperate to control cholera.

3. International Health Regulations
"The purpose of the International Health Regulations is to ensure the maximum security against the international spread of diseases with minimum interference with world traffic. Its origins date back to the 19th century when cholera epidemics overran Europe between 1830 and 1847. These epidemics were catalysts for intensive infectious disease diplomacy and multilateral cooperation in public health, starting with the first International Sanitary Conference in Paris in 1851.

Between 1851 and the end of the century, eight conventions on the spread of infectious diseases across national boundaries were negotiated. The beginning of the 20th century saw multilateral institutions established to enforce these conventions, including the precursor of the present Pan American Health Organization (PAHO).

In 1948, the WHO constitution came into force and in 1951 WHO member states adopted the International Sanitary Regulations, which were renamed the International Health Regulations in 1969. The regulations were modified in 1973 and 1981. The IHR were originally intended to help monitor and control six serious infectious diseases: cholera, plague, yellow fever, smallpox, relapsing fever, and typhus. At present, only cholera, plague, and yellow fever are notifiable diseases" (9).

In the mid-1990s, the WHO engaged in a major revision of the IHR. In 2005, the World Health Assembly voted and accepted the revised IHR. These Regulations became effective in June 2007. Some new concepts have appeared, but most revisions involve extensions of the previous Regulations, to put them in line with present demands for a global system for surveillance and control of international outbreaks. The IHR provide the only platform for international control of disease that could spread from one country to another. The main objective of the IHR is to control public health events that threaten the international community. The means to achieve this end include the following:

- Improved national surveillance in many countries
- A system to detect potentially international health-related events
- Use of modern communication tools
- Recognition of the fact that disturbance to free traffic constitutes an obstacle to reporting and mechanisms to counter this
- A set of generic rules to handle different kinds of urgent events
- A rapid mechanism to agree on appropriate levels of national protection within this set of rules

No isolated national control strategies will ultimately be successful. The only effective way for countries to protect their populations from international disease threats and their consequences is to collaborate on a global scale in order to develop global solutions.

During the revision of the IHR, the WHO created a number of working groups to help with the revision. One of these groups was the Transportation Working Group. The members of this group were representatives from member states along with subject matter experts. Two aerospace medicine specialists participated in the IHR revision as well as in the development of guidelines for its implementation. The knowledge of medicine coupled to the knowledge of the aviation industry makes the aerospace medicine specialist an ideal candidate to participate in this kind of deliberations. Both the public health authorities and the aviation industry benefit from this cooperation.

4. Guide to Hygiene and Sanitation in Aviation
The IHR refers to another WHO publication called "Guide to Hygiene and Sanitation in Aviation" (10) published in 1977. This is an excellent publication that can be very useful for the aviation industry. However, it needed to be updated. WHO recognized that the revision of this publication requires the participation of one or more aerospace medicine specialists to keep it practical and properly oriented. Therefore, it asked the Chief of the Aviation Medicine Section of ICAO and the Medical Advisor of IATA to be members of the reviewing working group. The revision process began in early 2007 and the publication of the first section of the book, now in a modular approach, is expected in mid 2008.

5. Roster of Experts
Article 47 of the IHR 2005 requires the establishment of a roster comprising experts in all relevant fields of expertise. The WHO has already recognized the need for aerospace medicine specialists and three of those specialists have been appointed to the roster. This is a positive

development for the aviation industry as it means that those specialists will be consulted when there is a health issue related to air transport. This approach will help reduce the risk of confusion and conflicting information when advice is given concerning health and travel.

International Travel and Health

The WHO produces a publication called "International Travel and Health" (11). The second chapter covers "Travel by Air: Health Considerations." The involvement of aerospace medicine specialists was significant for the 2005 edition when three (3) of them were on the writing committee, helping to deliver a much more accurate and up to date document. The publication was reviewed in 2007 and again WHO secured the participation of two aerospace medicine experts. As far as air travel is concerned, this publication has become one of the few reference documents that can be recommended to air travelers and physicians who provide advices to air travelers. It provides adequate information to assist them to make most decisions related to their air voyage.

Tuberculosis and Air Travel

In 1998, the WHO published a document to provide guidelines to health care workers and travelers regarding tuberculosis (TB) and air travel. The document is entitled "Tuberculosis and Air Travel: Guidelines for Prevention and Control." At that time, one aerospace medicine specialist was on the writing committee and two others were on the review committee. The document was welcomed by the aviation industry, but there was still some confusion between the practice and the recommendation regarding passenger contact tracing. Owing to particular circumstances at the time, this issue could not be developed further. Fortunately the WHO decided to publish a second edition in 2006 (12). Three aerospace medicine specialists participated as members of the writing committee. As the exchanges between the public health authorities and the aviation industry through aerospace medicine specialists had become more frequent, with both sides having a better understanding of each other's role, it was possible to establish the proper responsibility for passenger contact tracing in case of exposure, and eliminate the confusion from the first edition. While the airlines should cooperate to the best of their ability, it has been clarified that it is primarily the responsibility of the public health authorities to contact and advise the passengers who may have been exposed to TB. There may be a few exceptions to that rule, but in general the public health authorities have the knowledge, the experience, the resources, and the legal authority to undertake this task.

In spite of the excellent cooperation between all the authors during the review process for the second edition, another element of confusion was left in the hard copy version. Recommendation 5 states, "Physicians should advise TB patients who undertake **unavoidable** air travel of short duration (less than eight hours) to wear a surgical mask when possible or to cover the nose and mouth when speaking or coughing at all times during the flight." Although this may be scientifically defendable, it is not yet possible to recommend this as best practice because air travel of patients with active TB does not yet have universal acceptance by the medical profession and the traveling public. This approach is even more controversial since the advent of multiple drug resistant and extensively drug-resistant (XDR) TB. To limit the confusion, the authors agreed to include a note in the electronic version of the document that reads "Recommendation 5 is applied only on a case-by-case basis and subject to prior agreement of the airline(s) involved and the public health authorities at departure and arrival" (12). The future hard copy version will reflect this approach. A situation where there is a difference between the hard copy and the electronic copy of the same document is obviously not ideal. However, it highlights the significant difficulties in writing an international document and illustrates how good cooperation between the disciplines involved can provide an acceptable solution. Further, the increased understanding of the subject such discussion brings is likely to generate an even better outcome for the next shared project which has already started. Indeed, as a result of a few serious incidents involving XDR-TB and air travel that revealed some gaps in the current guidance material, WHO decided to revise the material one more time and added a few other key experts to the group involved in the previous edition. This next edition will be published in 2008. Along with the IHR review and the International Travel and Health project, this project further demonstrates the added value brought by the aerospace medicine specialists in the international arena.

World Health Organization Research into Global Hazards of Travel

In June 2001, prompted by the untimely death of a young woman from a pulmonary embolism after a long trip by air, the World Health Organization Research into Global Hazards of Travel (WRIGHT) project was established. "The project consists of a series of research studies to fill in the key information gaps in knowledge on the suspected link between air travel and venous thromboembolism. The studies, which cover epidemiological, clinical, and physiological aspects, will provide key information on the frequency of venous thromboembolism, the magnitude of its association with air travel, and the causal mechanisms with a view to developing prevention strategies for air travelers" (13). The two main participating centers are: the Leiden University Medical Center of Amsterdam, the Netherlands, and the University of Leicester, the United Kingdom. At the onset of the project, a Project Monitoring Committee was established and the two aerospace medicine specialist members of this committee were able to provide guidance on the operational and logistic aspects of the aviation industry to help shape the practical aspects of the research. They also committed to disseminate the results of this research once they would become available.

Because of funding difficulties the full project has not yet been completed, but some important results have been published (14–16). Furthermore, WHO just released the report of phase I of the project and it is available on their website (13).

UNITED STATES CENTERS FOR DISEASE CONTROL AND PREVENTION

The CDC is not an international institution *per se* but a national one. However, it deserves mention because of its international involvement and stature. Indeed the CDC supports the WHO and many countries' public health authorities, making it an important international player. A good example of one of their international services is their website on travel: http://wwwn.cdc.gov/travel/default.aspx.

There had been intermittent cooperation between some individual aerospace medicine specialists and the CDC for quite a while, but since 2003 and the SARS outbreak this cooperation has become routine. The CDC consults with aerospace medicine specialists both at the national and the international level on a regular basis and certainly for all matters involving air travel.

THE INTERNATIONAL AIR TRANSPORT ASSOCIATION

The IATA's primary goal is interairline cooperation for the purpose of "promoting safe, reliable, secure and economical air services for the benefit of the world's consumers." Founded in 1945 with 57 members representing 31 nations, it now has a membership of more than 240 airlines from more than 130 nations.

In its earliest days, IATA had an active medical activity to support the technical changes that were taking place in aviation. This activity declined in the 1980s and 1990s. More recently, however, IATA has reactivated its medical role in light of new public health and consumer issues. In 2001, IATA created a new Medical Advisory Group (MAG), consisting of 10 Medical Directors from major airline members of IATA. The selection of these Medical Directors is designed so that all major areas of the globe are represented.

In 2003, after SARS, it became evident that the MAG alone would not be sufficient to provide the regular service that IATA and its members needed. Indeed, as a result of the lessons learned from SARS, IATA established the position of Medical Advisor. This is a part-time consultant position that calls for a specialist in aerospace medicine. The current incumbent began working at the beginning of 2004. Because this is a fairly new international position, it is of interest to publish the following terms of reference:

- Develop industry positions on airline medical issues in association with IATA's MAG and other IATA departments
- Represent the industry with governments, the media, and other groups on airline medical issues
- Establish effective working relations with the WHO and other international bodies involved in airline medical issues
- Provide advice to member airlines on airline medical issues
- Provide expert advice to support products and services managed by IATA
- Develop and launch an IATA Training Course on management of airline medical issues;
- Develop and update IATA guidance materials, as required
- Act as Secretary to, and support the work program of, the MAG
- Coordinate the airline involvement in the airline health studies as may be required
- Provide other related services and advice, as required

From the outset, the focus of the Medical Advisor was on developing and maintaining working relations with the WHO, ICAO, and ACI, which has proved invaluable for all concerned. Excellent working relations were also developed with major national bodies such as the ECAC, the CDC, the Public Health Agency of Canada (PHAC), and many others. This approach fosters cooperation and stimulates consultation. As the "end user" of many aviation-related policies, IATA contributes a much-valued expertise in the development of such policies, because of its experience in their practical application.

With the WHO, the IATA Medical Advisor has actively participated in a wide range of projects: review of the IHR and guidelines generation, the International Travel and Health document, the Tuberculosis and Air Travel Guidelines document, and the WRIGHT project. During the IHR revision, it became evident that traveler contact tracing, which is very important with many communicable diseases, was often a problem after air travel. The WHO, through the Transportation Working Group, asked IATA and its Medical Advisor to develop a template for a PLC that would be recommended to member states. Although its use would not be mandatory, it was hoped that member states would accept it for use during a pandemic or following the discovery of any suspected communicable disease on board an aircraft when contact tracing was necessary, thereby bringing a degree of harmonization to an often haphazard process. To achieve this objective, all participants in the Transportation Working Group would publicize the document through their communication system (website, guidelines, etc.). This is an example of international cooperation that will facilitate contact of passengers who may have been exposed to a communicable disease that will clearly benefit the passengers, the states, and the airlines. As mentioned earlier, ICAO has included the PLC in its revised Annex 9. Although this move is an important step forward in favor of public health, it was realized from the beginning that it is likely an interim measure. Indeed, the ultimate answer to this difficult problem is likely to be electronic collection of the passengers' contact information. The IATA continues to work in that direction with its partners.

Another issue that came up during the IHR revision was the WHO publication "*Guide to Hygiene and Sanitation in Aviation*" (10). The issue had also surfaced at the same time from another angle. After performing some water sampling and testing on board aircraft, the U.S. Environmental Protection Agency (EPA) found some cause for concern; noting that 17% of the water samples showed that the bacteriologic quality of the water might be considered suboptimal. EPA stated that it would review its regulation on water quality on board aircraft and alluded that the new regulation may apply to all airlines flying to/from the United States. The IATA Medical Advisor suggested to the EPA that international cooperation works best in the international arena and proposed that the revised Guide to Hygiene and Sanitation of WHO may be the best answer to the question at hand and would avoid a proliferation of national regulations. The WHO will generate a panel of experts from the member states to review the Guide and it will become the accepted international norm, not only for water but also for food and waste disposal. IATA is supporting the WHO as necessary to develop new guidelines.

The IATA Medical Advisor also cooperates with the WHO on the issue of aircraft disinsection. This issue has been contentious for a long time and many countries still maintain the requirement of arriving aircraft to carry out disinsection procedures designed to prevent the transmission of insects that may carry disease (17). These disinsection procedures involve the spraying of an aerosol insecticide in aircraft compartments, including the passenger compartment. There are two basic methods of delivering the insecticide: spraying may be carried out while the passengers are on board and the doors closed, or it may be done while the passengers are not on board. This second method, called *residual spraying* leaves a residue on the aircraft surfaces and normally the procedure has to be repeated about every 8 weeks. Some countries allow the airlines to choose their preferred method, some do not. The most common pesticides in current use in aircraft disinsection are the synthetic pyrethroids, such as permethrin. They are synthetic analogs of pyrethrum extracts derived from the chrysanthemum, and are considered to be among the safest pesticides available for humans and the environment. However, susceptible individuals can experience hypersensitivity reactions such as itching, sneezing, coughing, and bronchospasm. This is why the WHO *Report of the Informal Consultation on Aircraft Disinsection,* sponsored by WHO (1995) (18) cautioned that some individuals may experience transient discomfort if exposed to aerosol spraying. Therefore, susceptible travelers are advised to call their airline well before departure and ask for specific information regarding possible disinsection procedures, in the event that they may wish to make alternate itinerary arrangements.

In spite of the low toxicity recognized by the scientific community, there are still many complaints from the passengers and the cabin crew. The IATA Medical Advisor and its partners in the WHO and the ICAO therefore continue to monitor and support research in new nonchemical methods of disinsection. One such method being considered is the so-called air curtain method that is designed to prevent insects flying into an aircraft by creating airflow out of the aircraft, which has a greater velocity achievable by the insect in question. So far it has not proved as simple and as effective a method as chemical spraying. However, research continues.

Another cooperative project underway between WHO, ICAO, CDC, EPA, aircraft manufacturers, and IATA is on aircraft disinfection. All the above stakeholders receive frequent questions from the users on acceptable methods and products for aircraft disinfection after a suspected or proven case of communicable disease. The issue is not simple because not only must the chosen disinfectant be effective against the relevant organism but it must also be compatible with safe use on an aircraft. The IATA is particularly interested in this project because all member airlines would benefit from a positive outcome of this cooperation that would reduce the current uncertainty about which disinfectants to use in which circumstances. The establishment of a small, international, advisory group that can provide rapid guidance in the event of a future outbreak of a new communicable disease would be of great value to the global effort in reducing the risk of disease transmission by air transport and would hopefully prevent the publication of conflicting information, which has occurred during previous health-related events.

As mentioned earlier, the IATA Medical Advisor is a member of the ICAO working group to address the threat of a human influenza pandemic on the aviation industry. In fact, the guidelines for suspected communicable diseases previously generated by the IATA were very useful in the process of developing the ICAO member states guidelines as well as in the process of developing the IHR implementation guidelines for member states. The IATA guidelines have been developed for use by nonmedical personal that cannot be expected to make a diagnosis but need advice on how to react appropriately with a sick traveler, especially if the sickness is a suspected communicable disease. The guidelines, which are updated regularly, can be found on the IATA website (19) along with several other pertinent information related to travel and health.

Building on the experience of providing *ad hoc* training on aerospace medicine for IATA's "Training and Development Institute" (ITDI), the need for a new course "Medical Issues in Aviation" has been identified by IATA. Furthermore, to continue to work in the spirit of international cooperation, IATA approached ICAO and suggested that a course be developed and delivered jointly by IATA and ICAO, possibly assisted by the WHO and the ACI. This would not only enlarge the pool of attendees but would also go a long way in facilitating the promotion of the message that international problems require an international approach by all the stakeholders involved and that the main international bodies are able and willing to work together. This would support several of ICAO and WHO programs, and demonstrate the willingness of member states of the UN to follow leadership of these UN agencies. The first course was given in Libreville, Gabon in 2007 and was very successfull.

As mentioned in his terms of reference, on a day-to-day basis, the IATA Medical Advisor provides advices to member airlines, supports other departments and/or other products of IATA, updates the IATA Medical Manual and the IATA web page on health, responds and comments on different states' proposed rule making and ICAO state letters, attends conferences, and makes many presentations on airline medical issues. The threat of influenza pandemic has been the topic of choice for those presentations during 2006. Finally, the Medical Advisor has been appointed to the IHR Roster of Experts.

The description of this new position of IATA Medical Advisor gives another example of the practice of aerospace medicine in an international setting, a unique and challenging practice environment. It also shows the significant involvement of the IATA in aerospace medical issues.

INTERNATIONAL FEDERATION OF AIR LINE PILOTS' ASSOCIATION

With the formation of ICAO after the Chicago Convention, pilot associations realized that they would require organized representation at an international level to participate in the formulation of international aviation regulations and policies. The International Federation of Air Line Pilots' Association (IFALPA) (20) was born in London, the United Kingdom, in 1948. Its mission statement: "to be the global voice of airline pilots, promoting the highest level of aviation safety worldwide, and providing services, support, and representation to all its Member Associations".

The Federation has more than 90 Member Associations, representing more than 100,000 pilots internationally. The IFALPA has a permanent observer on the ICAO Air Navigation Commission (ANC), and is therefore able to participate in the activities of the ANC, including the formulation and revision of the SARPs. The Federation liaises with many international aviation organizations, including the major international aeromedical scientific meetings. It does not have an aerospace medicine specialist on staff or on retainer, but it consults with aerospace medicine specialists when the topic under discussion requires such expertise. There are a number of airline pilots who are also trained in medicine who can assist the Federation in providing an aeromedical opinion from the pilot's viewpoint at international forums.

THE INTERNATIONAL AIRLINE PASSENGERS ASSOCIATION

As aviation travellers increased in great numbers, they realized that there was no voice to represent the airline passengers. Therefore in 1960 in New York City, the "Airways Club" was born. Later it became the International Airline Passenger Association (IAPA) (21) with global interests in areas such as safety, health and the cabin environment, and quality of passenger service on behalf of its present 400,000+ members from more than 200 countries. IAPA's head office is currently located in Dallas, Texas, with branch offices in London and Hong Kong. IAPA does not have an aerospace medicine specialist on staff or on retainer, but historically it has been interested in passenger health. IAPA usually sends a medical representative to international aeromedical meetings to represent their interests.

INTERNATIONAL ACADEMY OF AVIATION AND SPACE MEDICINE

The International Academy of Aviation and Space Medicine (IAASM) (22) was founded in 1955, to foster international cooperation and enhance communication among those devoted to the practice of aerospace medicine and its allied sciences, education, and research in this particular field. The objectives read as follow:

1. To promote the development of the scientific base of aviation and space medicine
2. To encourage and foster research in the fields of aviation and space medicine
3. To promote exchange of information, ideas, and experience in aviation and space medicine
4. To improve teaching of aviation and space medicine
5. To foster the training of experts (specialists) in aviation and space medicine
6. To facilitate international cooperation and exchange among individuals and organizations involved in aviation and space medicine
7. To provide an international source of recognized expertise in all areas of aviation and space medicine

The IAASM sponsors an annual International Congress of Aviation and Space Medicine (ICASM), hosted in a different country each year. Another major activity of IAASM is the awarding of a scholarship to a deserving candidate to further their studies in aerospace medicine at the postgraduate level. Scientific monographs are also published from time to time, usually based on the *André Allard Lecture*, given by a distinguished individual who is awarded the honor of delivering the lecture at the annual Congress.

The IAASM is managed by an Executive Council formed by 12 volunteer members who spend much of their free time in the development of aerospace medicine at the international level.

AIRLINES MEDICAL DIRECTORS ASSOCIATION

In existence since 1944, the Airlines Medical Directors Association (AMDA) was formed to facilitate communication and advancements in the field of aviation and occupational medicine pertaining specifically to the airline industry. Currently, the Association's membership includes more than 170 physicians representing medical departments of airlines internationally and other practitioners with an interest in airline safety. Activities of the AMDA include a popular annual 1-day Scientific Meeting held just before the Aerospace Medical Association (AsMA) Annual Scientific Meeting and an annual award to an individual for outstanding contributions and achievement in aerospace medicine.

AEROSPACE MEDICAL ASSOCIATION

From its early beginnings in 1929, under the guidance of Louis H. Bauer, M.D., when it was primarily an organization based in the United States, the AsMA (23) has grown to a membership approaching 3,000 representing more than 80 countries. The membership list includes aerospace medicine specialists, flight nurses, psychologists, physiologists, engineers, scientists, technicians, and researchers in every area related to aerospace medicine, aeronautics, astronautics, undersea medicine, and environmental health. The AsMA publishes a monthly professional peer-reviewed journal, *Aviation, Space and Environmental Medicine.* In addition, the AsMA holds an Annual Scientific Meeting, which is attended by representatives from every discipline involved in aerospace medicine, environmental health, diving medicine, civil and military operations, and many organizations from around the world.

Although the AsMA has its charter in the United States, it is an international association for all intents and purposes. Over the last decade, its officers have strongly encouraged international participation and two international members have been elected president during that period. The AsMA expertise and opinion are sought internationally and it produces position papers that have international impact.

CIVIL AVIATION MEDICAL ASSOCIATION

The Civil Aviation Medical Association (CAMA) (24) began in the United States as the Airline Medical Examiners Association in 1948, at a time when there were less number of private and civil AMEs who primarily examined airline pilots. In 1955, the Association became known as the present *CAMA*. The CAMA's membership consists mainly of aviation medical practitioners who work in the subject on a part-time basis. Many members are family practitioners (several are also private pilots) who have undertaken additional training in aerospace medicine and CAMA serves as a voice for such individuals. Although the organization began specifically to support the interests of the U.S. Civil AME, it now enjoys a wide international membership representing more than 50 countries and territories. The CAMA publishes a regular newsletter *Flight Physician* and holds an Annual Scientific Meeting dealing with aeromedical issues of interest to the private aeromedical practitioner. This meeting is held at an international location on every third year.

CONCLUSION

This section has reviewed the activities of the aerospace medicine specialist involved in a few important international organizations in the aviation sector. It is hoped that it has painted an accurate picture of this unique and challenging practice environment. In some cases, the aerospace medicine specialist uses his specialized aerospace medicine knowledge in his duties. In other cases, it is his knowledge of the aviation industry and environment coupled to his general medical knowledge that can be applied to find practical solutions to medical challenges such as public health issues. In all cases, to be effective, the aerospace medicine specialist must work with many other disciplines and other international bodies.

The author has retained the initial quote from the previous edition. Clearly the advent of aviation has abridged distance, made all parts of the globe accessible, brought men into closer relation with each other, and advanced civilization. However, as nothing is perfect in this world and as it is often remarked, advantages carry with them their dependant disadvantages. Abridging distances and making all parts of the globe quickly accessible, by bringing men into closer relation, may also rapidly spread diseases to distant locations. To deny this possibility or at least limit the potential damage, specialists of different disciplines and different parts of the world must work together in close cooperation and convince politicians to do the same. In this regard, the specialists in aerospace medicine's forward thinking approach should help, if not in totally achieving Octave Chanute's prediction, at least in protecting international health and bringing goodwill among men.

ACKNOWLEDGMENTS

I gratefully acknowledge the very valuable assistance of Dr. Anthony Evans, Chief, Aerospace Medicine Section, ICAO in reviewing this manuscript and making judicious comments. I also want to recognize the late Dr. George Takahashi, who was the author of this chapter in the previous edition.

REFERENCES

1. International Commission for Air Navigation. *Official bulletin No. 1*. Paris: July 28, 1922.
2. International Commission for Air Navigation. *Official bulletin No. 2*. London: Oct. 27, 1923.
3. Freer D. ICAO at 50 years: riding the flywheel of technology. *ICAO J* 1994: 19–32.
4. ICAO. *Implementation and celebration of international civil aviation day*. On Dec. 7, 2000. *PIO 12/2000*, Montreal, Canada: Dec. 2000.
5. International Civil Aviation Organization. *Manual of civil aerospace medicine*, 2nd edn. Document No. 8984–AN/895, Montreal, Canada: ICAO, 1985.
6. International Civil Aviation Organization. *Manual on prevention of problematic use of substances in the aviation workplace*. Document No. 9654, Montreal, Canada: ICAO, 1995.
7. International Civil Aviation Organization. *Assembly-35th session, report of the executive committee on agenda item 17 and 19*. A35-WP/343, P/75, 7/10/04, Resolution 19/1, 2004.
8. International Civil Aviation Organization. *Guidelines for states concerning the management of communicable disease posing a serious*

public health risk. http://www.icao.int/icao/en/med/guidelines.htm. Accessed on July 2nd 2007.

9. World Health Organization. *International health regulations*. www.searo.who.int/en/Section10/Section369_9695.htm. Accessed on July 2nd 2007.
10. Bailey J. *Guide to hygiene and sanitation in aviation*, 2nd edn. Geneva: World Health Organization, 1977.
11. World Health Organization. *International travel and health*. http://www.who.int/ith/en/. Accessed on July 2nd 2007.
12. World Health Organization. *Tuberculosis and air travel: guidelines for prevention and control*. http://www.who.int/tb/features_archive/aviation_guidelines/en/index.html. Accessed on July 2nd 2007.
13. World Health Organization. *The WRIGHT Project*. http://www.who.int/cardiovascular_diseases/wright_project/en/. Accessed on July 2nd 2007.
14. Schreijer AJM, Cannegieter SC, Meijers JCM, et al. Activation of coagulation system during air travel: a crossover study. *Lancet* 2006;367:832–838.
15. Toff WD, Jones CI, Ford I, et al. Effect of hypobaric hypoxia, simulating conditions during long-haul air travel, on coagulation, fibrinolysis, platelet function, and endothelial activation. *JAMA* 2006;295:2251–2261.
16. Cannegieter SC, Doggen CJM, van Houwelingen HC, et al. Travel-related venous thrombosis: results from a large population-based case control study (MEGA Study). *PLoS Med* 3(8):e307; DOI: 10.1371/journal.pmed.0030307. Accessed on July 2nd 2007.
17. World Health Organization (WHO). *International health regulations (1969)*, 3rd edn. Annotated ed, Geneva, Switzerland: WHO, 1983.
18. World Health Organization (WHO). *Report of the informal consultation on aircraft disinsection*. WHO/PCS/95.51. Geneva, Switzerland: WHO, November 1995.
19. International Air Transport Association (IATA). http://www.iata.org/whatwedo/safety_security/safety/health_safety/aviation_communicable_diseases.htm. Accessed on July 2nd 2007.
20. International Federation of Air Line Pilots' Associations. http://www.ifalpa.org/. Accessed on July 2nd 2007.
21. International Airline Passenger Association. http://www.iapa.com/index.asp. Accessed on July 2nd 2007.
22. International Academy of Aviation and Space Medicine. http://www.iaasm.org/. Accessed on July 2nd 2007.
23. Aerospace Medical Association. http://www.asma.org. Accessed on July 2nd 2007.
24. Civil Aviation Medical Association. http://www.civilavmed.com/. Accessed on July 2nd 2007.

CHAPTER 29

Aviation, Government Space, Biomedical Innovations, and Education

Jeffrey R. Davis

The human bird shall take his first flight, filling the world with amazement, all writings with his fame, and bringing eternal glory to the nest whence he sprang.

—Leonardo da Vinci

I confess that in 1901, I said to my brother Orville that man would not fly for fifty years . . . Ever since, I have distrusted myself and avoided all predictions.

—Wilbur Wright

The challenge of the great spaces between the worlds is a stupendous one; but if we fail to meet it, the story of our race will be drawing to its close. Humanity will have turned its back upon the still—untrodden heights and will be descending again the long slope that stretches, across a thousand million years of time, down to the shores of the primeval sea.

—Arthur C. Clarke

I don't think the human race will survive the next thousand years, unless we spread into space. There are too many accidents that can befall life on a single planet. But I'm an optimist. We will reach out to the stars.

—Stephen Hawking

We are at the beginning of a renaissance in aerospace medicine in the diversity and scope of practice. The following two chapters (29 and 30) highlight the emerging and potential developments in commercial aviation, government and commercial space programs, biomedical innovations, and education that will expand opportunities in, and biomedical applications for, aerospace medicine. The aerospace medicine practitioner will have to be a generalist and conversant in many existing and emerging fields of medicine, science and engineering, and developing aircraft and spacecraft, to provide the same level of care to future crews that is provided now. The challenge for educational programs is to provide the appropriate mix of academic knowledge and practical experiences to provide the new practitioner with the tools to succeed. Educational programs should strive to teach aerospace medicine as an integrated field from aviation to space.

DEVELOPMENTS IN AVIATION

General Aviation

One recent development in general aviation is the development of the sport pilot category with emergence of a new industry in light sport aircraft. Pilot medical and training requirements have been reduced for this category. Although the authors note that this rule has stimulated the light sport aircraft industry, they caution that the impact of reduced medical certification on aircraft mishaps from pilot medical or judgment issues is unknown at this time. Data will need to be collected and evaluated over many years to determine the accident/mishap rate, and root causes, in the sport pilot category (see Chapter 27). The hope is that an appropriate balance is found between stimulating general aviation and regulatory concerns.

Commercial Aviation

The 2007–2020 U.S. Federal Aviation Administration (FAA) Aerospace Forecast predicts that U.S. commercial aviation will carry 1 billion passengers by 2015 and 1.2 billion by 2020 (1). This forecast predicts 62.5 million take-offs and landings at U.S. towered airports during 2007, and 81.1 million by 2020. This represents an average growth of 1.4 million take-offs and landings per year during the forecast period. In addition, general aviation flying hours are also expected to increase 59% by 2020. The future may hold a greater number of aircraft flying point-to-point to decrease traffic in the terminal areas and increase efficiency. The predicted growth in U.S. civil aviation operations will also require an increase in the number of civil aviation flight crews and other support personnel, which, in turn, will increase the demand for aerospace medicine personnel to provide a broad spectrum of essential medical services.

Airport Medical Services

The expected growth in commercial civil aviation activity is likely to generate an increasing demand for airport emergency medical services to accommodate the medical needs of the increasing number of passengers who will be in transit through national and international airports. The availability of airport medical services will be particularly important considering the aging nature of the flying passenger population around the world and the increased potential for medical events in this population.

Very Light Jets

The introduction of very light jets (VLJs) is expected to revolutionize and promote the growth of the on-demand air-taxi transportation system and the corporate aviation sector (including fractional ownership programs). The FAA predicts that 250 VLJs will be added to the U.S. aircraft fleet in 2008, and the growth of this fleet will continue at a rate of 400 to 500 more per year through 2020. Most of these aircraft will be used for single-pilot commercial aviation operations that will emphasize the importance of ensuring pilot fitness for flight in view of the elimination of flight crew redundancy in some of these operations.

Commercial Transports

A new generation of comfort-oriented commercial transports such as the Boeing 787 (B-787) and the Airbus 350 (A-350) will fly at higher altitudes, at lower cabin altitudes, and will provide passengers with larger size passenger windows. The use of lower cabin altitudes will potentially benefit those passengers who have a variety of medical conditions that make them more susceptible to the adverse physiological effects of hypoxia, especially during long-duration flights. Flying at higher altitudes will result in less turbulence during flight, which will likely benefit those passengers who have a predisposition to motion sickness. The production of advanced aircraft that utilize a new generation of engines that are more fuel-efficient and reliable, incorporate more structural elements made of composite materials and alloys that are lighter and stronger, and take advantage of improved aerodynamic designs, will promote the continued expansion of ultra–long commercial flight operations. Appropriate safety procedures must be implemented to prevent any potential negative impacts of such long flights on flight crew performance, as well as the potentially adverse aeromedical impact of these flights on passenger health and comfort.

Aviation Safety

Civil aviation accounts for approximately 600 to 700 deaths annually and most occur in general aviation. The National Transportation Safety Board (NTSB) reported that in 2006 general aviation recorded the lowest number of accidents and fatalities in the last 40 years (2). Major air carriers operating larger aircraft between major airports have the lowest accident rates in civil aviation.

The NTSB list of "Most Wanted" air transportation safety improvements in the United States includes: (a) reduce the dangers to aircraft flying in icing conditions, (b) eliminate flammable fuel/air vapors in fuel tanks on transport category aircraft, (c) stop runway incursions and ground collisions of aircraft, (d) improve audio and data recorders and require video recorders, (e) reduce accidents and incidents caused by human fatigue, and (f) improve crew resource management in Part 135 operations (3).

Global Public Health

In Chapter 28, several new activities in international civil aviation were highlighted that are likely to expand. In 2004, the International Civil Aviation Organization (ICAO) assembly decided to add passenger and crew health in its definition of safety. The ICAO Council was charged to review existing, and develop new, Standards and Recommended Practices (SARPs) for global health issues including the potential for spreading communicable diseases by aircraft. The World Health Organization (WHO) developed a Transportation Working Group, and two aviation medicine specialists participated in the revision of the International Health Regulations (IHR). The revisions of the IHR seek to improve international surveillance and communication of public health issues. Therefore, the aerospace medicine practitioner will need substantial training in public health and an awareness of global health issues and surveillance mechanisms. Practitioners should anticipate consultation requests about global health issues with governments and the private sector as commercial aviation capacities increase for range, city connections, and number of passengers.

Military Aviation

In military aviation, the development of vectored thrust will produce aircraft with greater maneuverability that increases the potential for complicated acceleration environments (see Chapter 4). These multi-G environments likely will increase the physiological stress on the aviator requiring more sophisticated protective equipment that has the capability to automatically initiate action to protect the pilot. Aircrew will fly longer missions, and worldwide deployment will raise global public health issues (see Chapters 26 and 28). The development of Unmanned Aircraft Systems (UAS) produces concern over operator error and fatigue (see Chapter 23), and appropriate medical certification for operators (see Chapter 27).

DEVELOPMENTS IN GOVERNMENT SPACE PROGRAMS

Exploration beyond low Earth orbit (LEO) is once again at the forefront of planning for many nations. In the United States, National Aeronautics and Space Administration (NASA) released "*The Vision for Space Exploration*" (4) in February 2004 that initiated the development of the Constellation program within NASA. NASA programs will be presented in more detail (see subsequent text) with a brief description of some of the announced plans of other national space agencies. Several current planning efforts note that exploration is an international endeavor (see subsequent text).

James A. Baker Institute for Public Policy

In May 2007, the James A. Baker Institute for Public Policy, at Rice University in Houston, Texas, convened a 2.5 day summit about the future issues and challenges facing space medicine. This International Space Medicine Summit involved the participation of leading international members of the space community from government and academia. Perspectives were obtained from crewmembers, space medicine physicians, and biomedical researchers, as well as administrators and planners. Comprehensive panel discussions were held about the many challenges of long-duration space flight, especially when traveling beyond LEO. Published proceedings are pending from this workshop.

Center for Strategic and International Studies

The Center for Strategic and International Studies (CSIS) is a nonprofit, bipartisan public policy organization established in 1962 to address international policy issues. In the summer of 2003, CSIS began a Human Space Exploration Initiative (HSEI) to examine the future of human space exploration and the range of exploration visions from the world's space faring nations. The HSEI produced a 2005 report titled "The Still Untrodden Heights: Global Imperatives for Space Exploration" in the 21st Century" (5). According to the report, the purpose of the HSEI is "to explore new international perspectives on the future of human presence in space, assess their relative prospects, and build a new common global vision and agenda for the future of human space exploration." In 2004, the project team met with public and private members of the space community from around the world and held workshops on key issues.

The report noted five major recommendations that are briefly extracted here and the interested reader is referred to the full report that can be downloaded from the CSIS website (5).

1. Establish an International Year of Space Exploration in 2011 that will be the 50th anniversary of human space flight, commemorating Yuri Gagarin's and Alan Shepard's first flights.
2. Create a new International Space Governance Forum that could share best practices across borders among other suggestions.
3. Charter a new Global Venture Fund for space exploration to encourage innovative research.
4. Establish an International Prize for space exploration to reward and provide incentives for the greatest contributions to space exploration activities.
5. Make a renewed international commitment to space education through national governments and the private sector.

Global Exploration Strategy

Fourteen space agencies, through workshops in 2005 and 2006, collaborated in writing "The Global Exploration Strategy: the Framework for Coordination" May 2007 (6). Some of the space agencies that participated included the NASA, the China National Space Administration (CNSA), the European Space Agency (ESA), the Canadian Space Agency (CSA), the Japan Aerospace Exploration Agency (JAXA), and Roscosmos (Russia). The report concluded, "sustainable space exploration is a challenge that no one nation can do on its own." (6). These 14 space agencies developed the framework to present a vision for robotic and human space exploration, and to elaborate an action plan for sharing strategies so that all programs may be more effective and safe. The framework recommends a voluntary, nonbinding forum, the International Coordination Mechanism, through which nations can collaborate. A third workshop was held from May 30 to June 1, 2007 to discuss this Coordination Mechanism. In addition to science and technology development, the report notes that space exploration offers entrepreneurial opportunities by creating a demand for new technologies and services.

These reports reflect the international interest for collaboration in space exploration and represent the opportunities for peaceful collaboration in science and engineering. A collaborative model is needed for the sustainable exploration of space in which existing and future space agencies all participate.

U.S. Vision for Space Exploration and the National Aeronautics and Space Administration Constellation Program

In February 2004, NASA advanced The Vision for Space Exploration (4). The vision subsequently led to the Exploration Systems Architecture Study (ESAS) (7) that furthered the development of the exploration program at NASA later named *Constellation*. The Constellation program is responsible for the development and flight of a new crew exploration vehicle, Orion, and the new Ares family of launch vehicles. The Orion vehicle replaces the space shuttle, scheduled for retirement in 2010, at the completion of the International Space Station (ISS). The NASA 2006 Strategic Plan calls for operating the ISS through at least 2016. The Constellation program plans flight tests of the new Orion and Ares configurations with human piloted missions to the ISS by early to the middle of the next decade. This will restore the U.S. human space launch capability that ends with the retirement of the space shuttle in 2010. The Constellation program plans lunar landings and establishment of a more permanent lunar base and the NASA exploration website has the most current milestones and mission architectures (8).

NASA aerospace medicine experts are currently engaged in the development of standards and requirements for health care and environmental systems on long-duration human exploration missions. Additionally, there are standards and requirements for habitability and human factors design. Many challenges exist for the development of exploration aeromedical screening and health maintenance programs that provide for individual health and mission success. Issues such as the use of genetic screening and biomarkers for selection may provoke medical, ethical, and programmatic debates as to the application to aerospace medicine and space flight.

Russia

The Russian program plans satellites to the moon and Mars, as well as collaboration with partner space agencies to place scientific instruments on other projects such as the NASA Lunar Reconnaissance Orbiter (2008) and the NASA Mars rover (2009). For biomedical research, Russia has considered the launch of Bion spacecraft for orbital flights of 45 days that utilize organisms other than humans, and cell studies, to further understand the impact of space flight on living organisms. Russia will continue flying crewmembers and cargo to the ISS, using Progress and Soyuz vehicle launches, and conducting biomedical research on crewmembers during long-duration space flight. It is anticipated that ISS partners will share data from biomedical research projects. The Russian Institute of Biomedical Problems (IBMP) also plans a long-duration experiment of 520 days with six human research subjects to simulate a mission to Mars. This study is in collaboration with the ESA, and ESA and Russia will form a joint crew. Applications for interested volunteers were issued by ESA, June 2007, at the Paris Airshow; two precursor simulations of 105 days are planned in 2008 followed by a late 2008 or 2009 520-day simulation (9).

European Space Agency

At the time of this writing, the space shuttle program is scheduled to launch the Columbus module to the ISS in the fall of 2008 on STS 122. Two ESA astronauts are scheduled to fly; one will remain on the ISS for activation and checkout of the Columbus module. The module is the cornerstone of ESA's contribution to the ISS and contains several scientific racks for long-term research in space. ESA also plans to launch the Automated Transfer Vehicle (ATV) from its spaceport in Kourou, French Guiana. The ATV is a cargo vehicle that transfers payloads in a pressurized and conditioned environment. The first ATV named the *Jules Verne* is planned for launch in 2008 and will dock with the ISS after a 12- to 15-day flight. The Aurora Programme has the dual objectives to formulate and then implement a European plan for the long-term exploration of the solar system (10).

Japan (Japan Aerospace Exploration Agency)

Japan is one of the five partners in the ISS, which has flown astronauts on the space shuttle, and plans to fly a long-duration crewmember on the ISS. Japan is contributing the Japanese Experiment Module (JEM) named *Kibo* that enhances the long-duration space research capabilities on ISS. Japanese astronauts are scheduled to accompany the Kibo on space shuttle flights for the activation of the JEM, and for a 3-month mission to the ISS for the functional checkout of the JEM. JAXA's 2025 vision highlights development of technologies for lunar missions, and the continued development of space transportation systems among other objectives (11).

Canada (Canadian Space Agency)

The CSA astronauts have flown on space shuttle flights, and CSA has plans for long-duration flights to the ISS. Canada provides the mobile servicing system that currently consists of the robotic arm for the ISS (Canadarm2) and the Mobile Base System. The Canadarm2 installs and repositions modules and truss structure elements on the ISS. Dextre, the special-purpose dexterous manipulator, will be added to this system. The space shuttle Canadarm has a Canadian-made Orbiter Boom Sensor System (OBSS) installed to inspect the space shuttle for damage. Canada is developing concepts for participation in Mars missions and takes part in the Global Exploration Strategy discussions (12).

China (China National Space Administration)

The CNSA was formed in 1993 and is responsible for national space policy. China launched its first taikonaut, Yang Liwei, on October 15, 2003, on top of a Long March 2F rocket. Although it is difficult to say exactly what space missions China will pursue, they have publicized plans for an extravehicular activity (EVA) during an upcoming orbital flight, and have announced a possible space station, lunar base, and Mars mission.

India (Indian Space Research Organization)

The Indian Space Research Organization (ISRO) is India's national space agency. To date, the ISRO developed the Geosynchronous Satellite Launch Vehicle (GSLV). It has undergone several developmental flights since 2001 and others are planned in 2007. Chandrayaan is an unmanned probe to the moon, currently planned for 2008. This probe will be sent to lunar orbit and survey the surface of the moon in greater detail. NASA entered into an agreement to place two probes on board as payloads. Other proposals include Avatar, a reusable spacecraft using scramjet technology, for the launch of satellites.

Other Worldwide Space Agencies

NASA's office of external relations notes links to many other worldwide space agencies on dedicated websites (13). Other space agencies listed include Argentina, Australia, Bangladesh, Brazil, France, Germany, Hungary, Israel, Italy, The Netherlands, Norway, Ukraine, Korea, Spain, Sweden, Taiwan, United Arab Emirates, and the United Kingdom (13). Several of these countries are members of ESA and have their own national space agency.

Commercial Space Flight

Many exciting developments are forecast for the next few years in commercial space flight and the interested reader is referred to Chapter 30 for an expanded discussion of this emerging industry.

BIOMEDICAL ADVANCEMENTS IN RESEARCH AND TECHNOLOGY APPLICABLE TO AEROSPACE MEDICINE

Rapid advancements are anticipated in biomedical research and technology, which will provide new screening, diagnostic, and treatment capabilities for medical care that can be employed by the aerospace medicine specialist. These developments include the potential use of genetic screening and biomarkers in selection, development of nano health capabilities, and emerging technologies with greater miniaturization and capability of medical equipment.

Genetic Screening and Biomarkers

This text cannot cover the complexity of genetic screening and biomarkers other than to suggest future issues that may emerge in the practice of aerospace medicine. Genetic testing is "the analysis of human DNA, RNA, chromosomes, proteins, and certain metabolites in order to detect heritable disease-related genotypes, mutations, phenotypes, or karyotypes for clinical purposes" (14). Genetic characterization will be part of future health care, and the various phases of genetic screening will address heritable traits, specific gene expression and repression, and genome sequences. These emerging fields not only provide insight into the human genome and cellular manufacture of proteins but also the development of biochemical tests to detect the presence of genetic disease. Maturation of the technologies for genetic analysis has led to the emergence of high throughput analysis of peptide products. The science of proteomics greatly enhances opportunities for identification of medically useful biomarkers.

Predictive and presymptomatic types of testing are used to detect gene mutations associated with disorders that appear after birth, often later in life. Predictive testing can identify mutations that increase a person's chances of developing disorders with a genetic basis, such as certain types of cancer. For example, an individual with a mutation in the breast cancer 1 or 2 gene (*BRCA1 or BRAC2)* has an increased risk of breast cancer (15). Presymptomatic testing can determine whether a person will develop a genetic disorder before any signs or symptoms appear. The results of predictive and presymptomatic testing can provide information about a person's risk of developing a specific disorder, and assist with making decisions about medical care and aeromedical certification.

Future developments in genetic testing may lead to predictive tests of interest to aerospace medicine; perhaps individuals will be more or less resistant to the loss of bone mineral and structure upon exposure to microgravity. Other individuals may be more resistant to chromosomal and other damage from ionizing radiation exposure. Finally, many more chronic diseases may be linked to a genetic predisposition that could lead to individuals being screened out during selection if they have a greater likelihood of developing a career-ending disease. Alternatively, developments in genetic screening may lead to new treatment modalities that permit an individual with a chronic disease to function normally.

Many ethical dilemmas will emerge such as whether the predictive value and reliability of a test in making a high-stakes career decision for an aviator (selection screening) are high enough to warrant testing. Alternatively, would more skills in aviators be lost due to this screening and what is the right "trade" for an organization that desires to select healthy candidates yet not lose applicants with valued skill sets. What is the appropriate counseling for these individuals and what emotional support will be available when conveying the results of these tests? Are these tests only warranted in certain long-duration, high-stakes missions such as a mission to Mars? These issues will need to be addressed in many bioethical forums over the next decades.

Incentives are being developed to stimulate this field. One example is the Archon X PRIZE for Genomics announced on October 4, 2006. This prize is the second to be offered by the X PRIZE Foundation. The goal of the Archon X PRIZE for Genomics is to greatly reduce the cost, and increase the speed of human genome sequencing, to create a new era of predictive and personalized medicine (16). The Archon X PRIZE for Genomics, a joint effort of the X PRIZE Foundation and the J. Craig Venter Science Foundation, is a $10 million prize to be awarded to the first team to successfully sequence 100 anonymous human genomes in 10 days at a recurring cost of no more than $10,000 per genome (17).

Nanohealth

Nanohealth is a new term that incorporates the use of nanotechnology in medicine. The promise of this field is to develop diagnostic and treatment modalities at the molecular level. Strategies address the interfacing of cells and tissues with biocompatible materials and electronic systems to develop implantable as well as noninvasive devices. These emerging technologies may eventually assess real-time DNA damage, in drug delivery, multianalyte medical monitoring, and externally triggered interventions on an "as needed" basis. Future astronauts on long-duration missions may be able to carry some aspects of an individualized pharmacy in their cells. These technologies may truly alter the way medicine is practiced, and the aerospace medicine professional should be aware of the potential application of these technologies especially in remote, isolated missions where limited weight, volume, and power constrain the medical capabilites provided.

Medical Equipment Technologies

Many groups focus on the development of innovative biomedical equipment for the diagnosis and treatment of illness and injury. Some involve the intentional combination of medicine and technology, such as Bio-X at Stanford University or the Center for Integration of Medicine and Innovative Technology (CIMIT) in Boston that facilitate biomedical innovations. A complete discussion of these technologies is beyond the scope of this text but the aerospace medicine specialist should anticipate having many more tools in the future that may be included in aerospace medical missions to remote, isolated environments. Further, the specialist needs to be involved in early design discussions of new equipment to ensure applicability to the aerospace medical practice. Future astronauts on the moon or Mars likely will have sophisticated medical systems due to breakthroughs in design of small, lightweight, low-power, noninvasive devices.

EDUCATION

Residency Training Programs

In the United States, aerospace medicine is a specialty area of preventive medicine, and certification may be sought by the applicant from the American Board of Preventive Medicine (ABPM), one of 24 medical certification boards in the United States. To apply for certification, an applicant must complete a clinical year through an appropriately accredited program in the United States or Canada, and a 2-year training program in aerospace medicine consisting of an academic and practicum year (18). For many programs, completion of the academic year leads to conferral of the Master of Public Health (MPH) degree. This latter degree is important as practitioners will be challenged by public health concerns of global commercial and military aviation, and possibly by commercial space flight with point-to-point transportation, in the coming decades.

Formal training in aerospace medicine is only available in a few locations worldwide. In the United States, training may be received from the U.S. Air Force (San Antonio, Texas) and U.S. Navy (Pensacola, Florida) programs, (the U.S. Army utilizes the U.S. navy training program), and also at two NASA sponsored programs at Wright State University (Dayton, Ohio) and the University of Texas Medical Branch (UTMB, Galveston, Texas). These programs fulfill the requirements of the ABPM.

Aerospace Physiology

Training and fellowships of varying length are available at some institutions in the United States including the Vanderbilt Center for Space Physiology and Medicine, the National Space Biomedical Research Institute located at the Baylor College of Medicine, and a space physiology course at UTMB; the latter two programs work closely with the NASA Johnson Space Center. The United States Air Force (USAF), United States Navy (USN), and FAA, offer a variety of aerospace physiology courses of varying length for multiple disciplines. The Florida Space Grant Consortium offers the Space Grant Fellowship Program (SGFP) that provides an academic year fellowship stipend of $20,000 for full-time doctoral study renewable for 2 years; or $12,000 toward full-time Master's study, renewable for 1 year (19). Space medicine and space life sciences are some of the qualifying areas of study that can be considered by this program. This program also works closely with the NASA Kennedy Space Center in several key areas.

Certificate and Diploma Programs

The USAF and USN also offer short-courses for initial training of flight surgeons among other specialty certificate programs including an international aerospace medicine course at the USAF known as *Advanced Aerospace Medicine for International Medical Officers* (AAMIMO). Other training programs include the Aviation Medicine program at King's College London, of the University of London, leading to a Diploma in Aviation Medicine (DAvMed). This course originated at the Royal Air Force Institute of Aviation Medicine and was transferred to King's College in 1998. The course-work takes 6 months to complete beginning each January, and the diploma is conferred by the Faculty of Occupational Medicine of the Royal College of Physicians (London) following successful completion of faculty examinations. Basic and advanced courses are also offered in collaboration with the United Kingdom Civil Aviation Authority (CAA) to fulfill the requirements of the European Joint Aviation Authorities (JAA). Successful completion can lead to consideration of becoming an aeromedical examiner. In the United States, the FAA conducts basic and specialty refresher courses for training civilian aviation medical examiners. The basic course is 4.5 days long. The FAA currently has approximately 4,800 trained AMEs in nine regions in the United States, 410 International AMEs in 91 countries, and 400 Federal AMEs. A 3-day basic and advanced training course in aviation medicine is also offered by the JAA in The Netherlands.

Clerkships for medical students and residents exist at the NASA Johnson Space Center for two, 4-week offerings each year. The UTMB also offers a 4-week short course in aerospace medicine every summer. The NASA Kennedy Space Center offers a summer internship program for undergraduate students, and the USAF and USN programs offer clerkships for medical students and residents.

Future planning must consider the adequacy of training programs. U.S. residency aerospace medicine programs are specialty areas of preventive medicine dependent on the sponsoring agencies (military and NASA) for continued existence. With the reduction in research funding within the military, NASA and the FAA, there may be insufficient resources to train the next generation of research scientists conducting bench research in aerospace physiology and medicine. Thoughtful planning is necessary in a multiagency forum to make sure these research capabilities are not lost at a time when the variety of aerospace environments are expanding from the private sector with private commercial space flight, as well as exploration programs with the potential for international collaboration.

SUMMARY

This chapter has highlighted future developments and issues in aviation, government space programs, biomedical research and technology development, and education that may impact the future practice of the aerospace medicine specialist. The specialist will need to be a well-informed generalist in many fields of science, medicine, and engineering, to bring the best applications to bear to provide for the health, safety, and performance of future aviators, astronauts, cosmonauts, taikonauts, and private citizens. These developments truly reflect a renaissance in the field of aerospace medicine to be able to utilize rapidly emerging research and technologies in ever more diverse and challenging environments in commercial and military aviation, and government and commercial space flight. Multiagency discussions are essential to insure the adequacy of training programs for practitioners of aerospace medicine including physicians, biomedical researchers, and biomedical engineering among other degree fields. Indeed, the future is bright for aerospace medicine; our obligation as current leaders in the field is to provide for the training of the many next generations that will be challenged by commercial and government aviation and space flight.

> *Leaders are the ones who keep faith with the past, keep step with the present, and keep the promise to posterity.*
>
> —*Harold J. Seymour*

> *When once you have tasted flight, you will forever walk the earth with your eyes turned skyward, for there you have been, and there you will always long to return.*
>
> —*Leonardo da Vinci*

ACKNOWLEDGMENTS

I would like to recognize the contributions of Dr. Melchor Antuñano for his thoughtful consideration of future developments in civil aviation.

REFERENCES

1. Federal Aviation Administration. *FAA aerospace forecasts: fiscal years 2007–2020*. Available at www.faa.gov/data_statistics/aviation/aerospace_forecasts/2007–2020/, (last accessed September 3, 2007).
2. National Transportation Safety Board. NTSB news—annual statistics show continued improvement in aviation safety. Available at: http://www.ntsb.gov/pressrel/2007/070313.htm, (last accessed September 3, 2007).
3. National Transportation Safety Board. *NTSB most wanted transportation safety improvements: aviation issue areas.* Available at: www.ntsb.gov/recs/mostwanted/aviation_issues.htm, (last accessed September 3, 2007).
4. http://www.nasa.gov/mission_pages/exploration/main/index.html, (last accessed July 15, 2007).
5. http://www.csis.org/component/option,com_csis_pubs/task,view/id,1861/type,1/, (last accessed July 15, 2007).
6. http://www.jaxa.jp/press/2007/05/20070531_ges_e.pdf, (last accessed July 15, 2007).
7. http://www.nasa.gov/mission_pages/exploration/news/ESAS_report.html, (last accessed July 15, 2007).
8. http://exploration.nasa.gov/, (last accessed July 15, 2007).
9. http://www.esa.int/esaCP/SEMAJPXXV2F_index_0.html, (last accessed July 15, 2007).
10. http://www.esa.int/SPECIALS/Aurora/ESA9LZPV16D_0.html, (last accessed July 5, 2007).
11. http://www.jaxa.jp/about/2025/index_e.html, (last accessed July 15, 2007).
12. http://www.space.gc.ca/asc/eng/default.asp, (last accessed July 15, 2007).
13. http://www.hq.nasa.gov/office/hqlibrary/pathfinders/intlag.htm\#CN), (last accessed July 15, 2007).
14. Holtzman NA, Watson MS, eds. *Promoting safe and effective genetic testing in the United States: final report of the Task Force on Genetic Testing*. Baltimore: Johns Hopkins University Press, 1999.
15. http://www.cancer.gov/cancertopics/factsheet/Risk/BRCA, (last accessed July 15, 2007).
16. Editors note. *Rejuvenation Res* 2007;10(2): 237–242.
17. http://genomics.xprize.org/, (last accessed July 15, 2007).
18. http://www.abprevmed.org/, (last accessed July 15, 2007).
19. http://fsgc.engr.ucf.edu/programs/fellowships.html, (last accessed July 15, 2007).

CHAPTER 30

Commercial Human Space Flight

Melchor J. Antuñano, James M. Vanderploeg, Richard T. Jennings, Elizabeth E. Richard, and P. Vernon McDonald

I never think of the future. It comes soon enough.

—*Albert Einstein*

Although humankind has long dreamed of flying into space, we are only now on the verge of seeing these possibilities become a reality for more than a privileged few. Until recently, space flight has been limited to government-sponsored astronauts, cosmonauts, and taikonauts, and several citizens who could afford the multimillion dollar cost. However, we are now embarking on a new era in which many people will have the opportunity to travel into space. As noted in Chapter 29, the emergence of the commercial human space flight industry will significantly affect the field of aerospace medicine. In the future, aerospace practitioners will be confronted with health issues related to a wide variety of commercial space applications including orbital flights and suborbital flights with varying flight profiles and durations supporting activities such as space tourism; orbiting research and industrial laboratories; on-orbit assembly, repair, and provisioning facilities; and differing in-flight and ground support health and medical capabilities for each. This chapter will challenge the reader to consider how best to prepare for and address these new opportunities as a human space flight risk manager of the future.

THE COMMERCIAL HUMAN SPACE FLIGHT MARKET

Various forces will influence the ongoing development of the commercial human space flight industry. Although major technologic advances will not be required, improvements in design to make commercial spacecraft safe and reliable, an injection of institutional funding sources, and competition to drive prices down will all contribute to commercial feasibility. Additional drivers for development include the availability of orbital destinations such as space hotels and laboratories, a demand for new commercial space applications, and spaceports that can accommodate suborbital, orbital, and/or point-to-point transportation. Development of the orbital market will also benefit from the emergence of cost-effective launch capability spurred by government commitments, as well as a successful suborbital tourism market.

Although the numbers of space flight participants flying to the International Space Station (ISS) will remain very low, limited by the availability of launches and the multimillion dollar cost, the prospects of suborbital flights for $200,000 or less will open the doors to thousands of participants. Demand for space tourism appears promising. A 2006 Futron/Zogby survey projected 13,000 suborbital space flight participants per year by 2021, with projected annual revenue of more than $650 million in 2021 (1). Virgin Galactic, a leader in the emerging suborbital tourism market, had 100 passengers signed up who had already paid the full $200,000 fare by the end of 2006—well before the planned test flight program and maiden flight scheduled at least 2 years in the future. As of 2007, a total of 200 people from 30 countries had signed up to fly on Virgin Galactic's suborbital flights (2).

For suborbital space tourism to be successful, however, prices will need to come down. Key to this will be space vehicles that can fly repeatedly without requiring downtime for refurbishment and repair, and vehicles that have demonstrated safety and reliability records. Government may also spur development of the commercial industry by contracting commercial companies to deliver passengers and cargo to the ISS and other government space facilities. This will allow national space agencies to concentrate development on exploration initiatives to the moon and

Mars, thereby stimulating the growth of the low Earth orbit (LEO) commercial market for human space flight.

EVOLUTION OF COMMERCIAL HUMAN SPACE FLIGHT

Although the definition of what truly constitutes a "commercial" space flight participant can be debated, space flights including noncareer crewmembers perhaps began with Charlie Walker. Confirmed by National Aeronautics and Space Administration (NASA) in 1983 as the first industrial payload specialist, Mr. Walker accompanied the McDonnell Douglas continuous flow electrophoresis (CFES) equipment as a crewmember on space shuttle missions STS-41-D, STS-51-D, and STS-61-B from 1984 to 1985. The Russian space program flew a number of crewmembers from other countries to its space stations, but the first commercial cosmonaut may have been Toyohiro Akiyama. The Tokyo Broadcasting System reportedly paid $28 million for his flight to the MIR in 1990, where he spent 1 week and provided daily television broadcasts. A consortium of British companies paid for British chemist Helen Sharman to fly to the MIR in 1991. The Russian space program, in conjunction with Space Adventures, then began to fly paying passengers to the ISS with the flight of Dennis Tito on April 28, 2001. At the time of this publication, an additional four space flight participants had been launched on Soyuz spacecraft and spent 10 days in orbit on the ISS including Mark Shuttleworth, Gregory Olsen, Anousheh Ansari, and Charles Simonyi.

While private space flight using privately developed space vehicles has been discussed for decades, perhaps the first step toward a real industry occurred when the Ansari X Prize competition ($10 million) was announced by Peter Diamandis in 1995 and subsequently awarded in 2004. The X Prize was similar to early 20th-century aviation prizes such as the $25,000 Orteig Prize won by Charles Lindbergh for his solo flight across the Atlantic Ocean. To win, a nongovernment organization had to launch a reusable human-piloted spacecraft into space, twice, within 2 weeks. The prize was won using the experimental spacecraft Space Ship One developed by Burt Rutan of Scaled Composites; the technology is owned by a Paul Allen company (Mojave Aerospace Ventures). The two flights were piloted by Mike Melvill and Brian Binnie.

At the time of this publication, the next X Prize competition, the $2 million Northrop Grumman Lunar Lander Challenge, will be competed in New Mexico in October 2007. While the original X Prize was privately funded, this one is sponsored by a major aerospace company and funded by NASA. Contestants will develop and prove concepts for space vehicles that could safely ferry humans or cargo back and forth between the lunar surface and lunar orbit.

In late 2004, Sir Richard Branson's Virgin Galactic announced a collaboration with Burt Rutan to fly tourists into space using a scaled-up version of Space Ship One. Space flights for regular passengers are anticipated to begin in the 2009 to 2010 timeframe. Space Ship Two will be carried by White Knight II and climb to an altitude of approximately 100 km with a total flight duration of 2.5 hours (Figure 30-1). These suborbital flights will have a period of weightlessness of 4 to 5 minutes; the precise duration being driven by the altitude achieved. Initially launching from the Mojave Spaceport in CA, Virgin Galactic will ultimately be headquartered and launch out of Spaceport America in New Mexico.

Blue Origin, founded by Jeff Bezos of Amazon.com, seeks to lower the cost of suborbital space flight utilizing a different flight profile. Blue Origin is developing a vertical take-off and landing craft named New Shepard (3). This craft reached a height of 285 ft and successfully landed on November 13, 2006, and completed a second test flight in March 2007.

Other companies in the suborbital tourism market include Armadillo, BensonSpace, Myasishchev, PlanetSpace, Rocketplane/Kistler, Starchaser Industries, TGV Rockets, and X-Cor. A recent entry into this market worth noting came from European Aeronautic Defence and Space Company (EADS) Astrium. This announcement is significant because EADS is one of the largest aerospace companies in the world and reports indicate the cost of their program to be $1 billion. Several companies worldwide are also developing orbital space tourism capabilities, some facilitated by NASA Space Act Agreements (SAAs) as described in the subsequent text.

Orbital developers include BensonSpace, Energir Kliper, PlanetSpace, Rocketplane/Kistler, Shenzhou, Soyuz, SpaceX, Excalibur Almaz, and Transformational Space. Also, Space Adventures, who launched the first space tourists to the ISS on Soyuz spacecraft, announced plans in 2007 for additional orbital flights and circumlunar flights for a listed fee of $100 million, and hopes for a first tourist spacewalk from the ISS in 2009.

Other developers envision orbital destination tourism and other human-rated orbital commercial facilities such as Bigelow Aerospace (founded in 1999 by Budget Suites founder Robert Bigelow) using expandable modules such as Genesis I. This module was launched on July 12, 2006, from Russia and is a one-third scale mockup of a future module. Genesis I has a useable habitable volume of 11.5 m (3), and is currently in LEO.

In late June 2007, Bigelow Aerospace launched its second small-scale inflatable module aboard a Russian rocket. The module, Genesis 2, successfully joined Genesis 1 in orbit, and the company plans to launch a larger module in fall 2008. Bigelow is aiming to launch human-habitable modules into space for use as orbital accommodations by 2012. Future on-orbit applications may include pharmaceutical development, materials manufacturing, biotechnology research, industrial facilities, or materials manufacturing. On-orbit assembly, repair, and provisioning capabilities will likely be required for the development of orbiting hotels, industrial operations, research facilities, and other complex structures. In addition to the medical screening and training required for space flight participants engaging in tourism, these human-tended

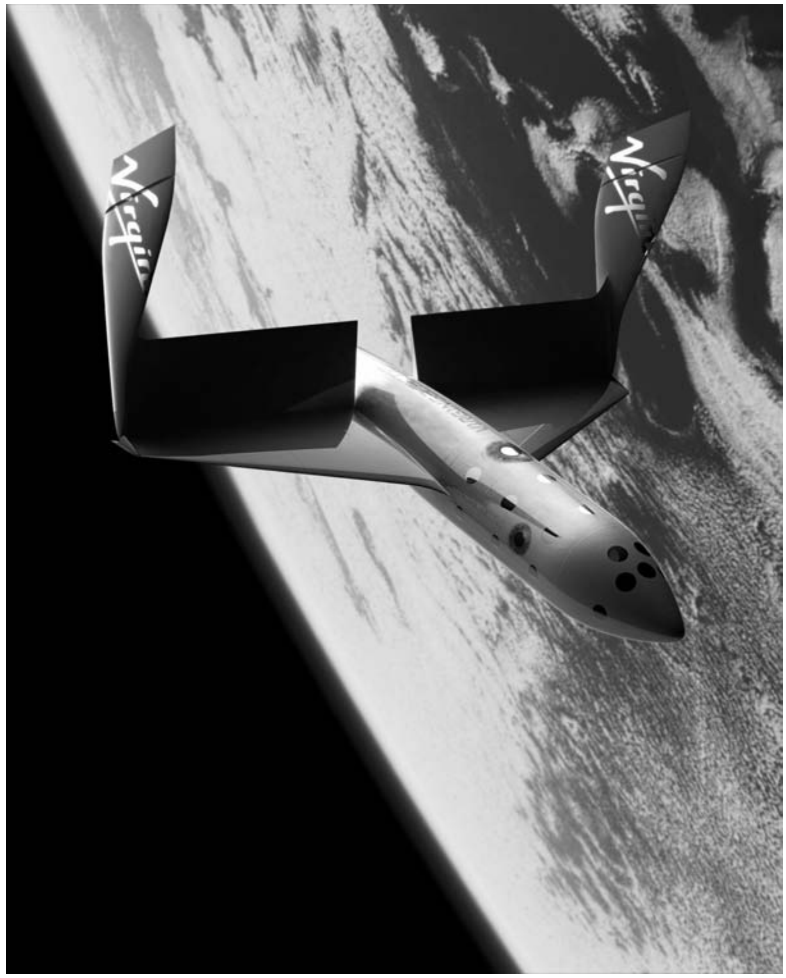


FIGURE 30-1 A conceptual image of Space Ship Two, the advanced passenger-carrying version of Space Ship One, showing the space ship in its feathered position with the actual image of earth as seen by Brian Binnie on his X prize winning flight. Courtesy of Virgin Galactic.

facilities will require on-orbit health monitoring and occupational medicine services.

Another type of commercial space transit, suborbital point-to-point transportation, may emerge in parallel with commercial orbital transport to deliver cargo or people from one place on Earth to another faster than ever before—with the potential to go halfway around the world in 40 minutes. Once the technology is available for suborbital flight, point-to-point travel will require the ground infrastructure to permit launch and landing in different locations.

Impact of Government Agency Programs

While suborbital tourism is being developed and funded by private sources, government agencies may provide funding that serves as a catalyst for commercial orbital space flight development. The 2005 NASA Authorization Act calls on NASA to advance space commerce. NASA announced a competition totaling $500 million for Commercial Orbital Transportation Services (COTS) to take cargo and possibly crew to the ISS, with a goal of acquiring reusable rockets that dramatically cut the cost of launching payloads into space. Two companies successfully competed for this initial funding, and NASA signed SAA on August 18, 2006 with Space Exploration Technologies (SpaceX) and Rocketplane-Kistler (RpK) to develop and demonstrate the vehicles, systems, and operations needed to support an orbital facility such as the ISS. NASA subsequently signed unfunded COTS SAAs with T-Space and PlanetSpace in February 2007.

In June 2007, NASA signed nonreimbursable SAAs with three additional companies: SpaceDev, SPACEHAB, and Constellation Services International (CSI). These companies will also work to develop and demonstrate the vehicles, systems, and operations needed to transport cargo to and from a LEO destination. The final option of the COTS program is for crew transport, and several of the companies plan to include this capability.

Infrastructure Requirements for Commercial Human Space Flight

While space flight operators focus on vehicle design and testing, commercial human space flight services are also emerging to address various aspects of human risk management and the provision of services and products to prepare space flight participants for flight. Tens of companies are offering new space launch services, and marketing access to Russian launchers. There are space tourism, zero-g simulation and training companies, infrastructure/subsystems engineering companies, commercial space exploration companies, and companies offering medical screening and health risk management services.

Critical to the infrastructure of each of these human space flight market segments will be the availability of spaceports to provide a convenient place from which to launch and land. Launch pads will be needed for orbital space vehicles, and the spaceports will have to be large enough and located such that human lives would not be endangered should an accident occur on the launch pad. Long runways to facilitate winged launch vehicles will be required for suborbital space vehicles and the hypersonic aircraft used for point-to-point suborbital transportation.

The New Mexico Space Authority is on schedule to open Spaceport America in Las Cruces, New Mexico, in 2008 with Virgin Galactic as the anchor tenant. Six commercial spaceports, located in Alaska, California (Vandenberg Air Force Base and Mojave Airport), Florida, Oklahoma, and Virginia, currently have Federal Aviation Administration (FAA) launch site operator licenses. Oklahoma received its launch site operator license in 2006. Several other commercial spaceports are under active development, including sites in New Mexico and Texas. Spaceports to support commercial human space flight are also under development or being considered worldwide in locations such as Australia, Canada, Russia, Singapore, Sweden, and the United Arab Emirates.

REGULATORY ENVIRONMENT: EVOLUTION OF SPACE FLIGHT GUIDELINES, STANDARDS, AND CERTIFICATION

Commercial Space Flight Regulation

The Office of Commercial Space Transportation (referred to as AST) in the FAA was created by the Commercial Space Launch Act of 1985; the AST is responsible for licensing private space vehicles and spaceports within the United States among other responsibilities. Congress also mandated regulations for commercial space flight through specific legislation entitled the Commercial Space Launch Amendments Act of 2004 (4). These regulations (*Human Space Flight Requirements for Crew and Space Flight Participants*) (5) were published by the FAA as a final rule in December 15, 2006 to protect the safety of the uninvolved public and enable passengers to make informed decisions about their personal safety. They do not impose health and medical standards for passengers or "space flight participants" but rather provide criteria for medical screening in the form of guidelines. There are a number of reasons for this approach including the regulatory restrictions placed on the FAA by the U.S. Congress, the state of the art in defining the medical risks of space flight for a population much broader than the historical space traveler, and the desire on the part of the commercial operators to not be restricted by a set of medical standards that might unnecessarily limit the breadth of their customer base. However, the rules do require operators to inform passengers about the general risks of space flight and the specific risks of space travel in the operator's vehicle. Other aspects of the rules include medical qualifications of the crew and requirements for training.

Commercial companies are currently developing medical screening programs for crew and space flight participants and some have held workshops to develop medical screening guidelines (see subsequent text). The aerospace medicine professional could reasonably anticipate screening some of these crew and space flight participants over the next decade depending on the volume and scope of screening developed. FAA aviation medical examiners (AMEs) may require special training to conduct these space flight examinations for crews in the future.

Medical Screening of Crew and Space Flight Participants

The sections discussed earlier highlight a wide range of possibilities for human commercial space flight with the potential for thousands of people participating in suborbital and orbital flights. The participation of large numbers of private citizens raises many questions for the medical community in terms of how to accurately assess the risks posed to a particular space flight participant. The philosophy behind medical screening protocols for space flight participants is very different from government-sponsored astronauts, cosmonauts, or taikonauts. Whereas government-sponsored crewmembers must meet medical standards aimed at optimizing health and performance to carry out mission-specific tasks over an extended period of time, space flight participants are passengers with no required duties, and in the case of suborbital flights, very brief exposure to the space environment. While government agencies must fly a few well-trained individuals to carry out strictly defined objectives and potentially demanding tasks to achieve mission success, private operators want to fly as many people as safely as possible to achieve financial viability. These differences necessitate a very different approach to medical screening.

Government programs, such as the flights aboard the Russian Soyuz vehicle or the space shuttle to the ISS, have set very strict medical standards for any flight participant whether career astronauts or single-time flyers who can afford the cost of access. An important precursor to setting standards for any program is establishing the level of risk that program is willing to tolerate. For example, in 2002, the mean age of career astronauts was 44 [standard deviation (SD) = 6.7] for women and 44.5 (SD = 5.6) for men (6). Their medical status is very well known and strict medical standards limit those who qualify. By contrast, the likely passenger distribution for commercial space flight will include individuals from 18 years (or the age of consent) to older than 90 years* with a very wide range of medical conditions who may make only a single flight. The challenge

*Richard Branson of Virgin Galactic has said he plans to be on the first commercial Virgin Galactic flight along with his children and parents—including his 91-year-old father. (see http://news.bbc.co.uk/2/hi/uk_news/4178747.stm), Sunday, 16 January, 2005, for the aerospace medicine specialists working in the new era of commercial human space flight will be to define medical protocols and assessment methodologies to provide a pragmatic assessment of risk. This task needs to be performed with the objective of enabling this broad range of people to achieve their dream of space flight should they choose to be exposed to these risks.

Given a defined risk tolerance, NASA has had a relatively long history considering medical standards for nonprofessional flight crew. In the mid-1980s, NASA developed Class IV medical standards for teachers, news media, and other potential passengers making a single space flight but these were never used. NASA ultimately certified these nonprofessional space flyers as payload specialists and used Class III medical standards. The next major impetus for the evolution of NASA flight certification standards came about because of Dennis Tito, when he began training for a flight to the ISS. In response to the introduction of space flight participants taking flights to the ISS, the Russians (for the Soyuz vehicle flights) and the Multilateral Medical Operations Panel (MMOP) (for the ISS) developed medical standards for use in evaluating and approving commercial space flight participants. These standards, approved in 2002 and revised in 2007, are known as *Medical Volume C* (see Chapter 11) and are implemented under the auspices of the Multilateral Space Medicine Board (MSMB). The board comprises medical representatives from all five ISS partners—NASA, Canadian Space Agency, Russian Space Agency, European Space Agency (ESA), and Japan Aerospace Exploration Agency (JAXA). The ISS partners plan a public release of these standards to further encourage the development of the commercial space flight industry.

Several organizations, including the Aerospace Medical Association, the Space Transportation Association, and the International Academy of Astronautics have also been involved in discussions of medical standards for the noncareer astronaut. During 2001, a task force was formed under the auspices of the Aerospace Medical Association to establish guidelines for private businesses, medical providers, and those planning to be a space tourist. The product of the efforts of this task force was published in October 2001 (7) and largely consisted of lists of medical conditions that would disqualify someone from acceptance as a space flight participant for orbital flights of 1 to 7 days' duration. Subsequently, the task force reconvened in 2002 to focus on less stringent medical screening for short-duration suborbital space flights. The results of these deliberations were published as a position paper in November 2002 (8) and were based on the following five assumptions.

1. The space vehicle interior will be small and confining with a capacity for four to six passengers.
2. The flight will be suborbital of 1 to 3 hours duration including approximately 30 minutes in microgravity.
3. The cabin will be pressurized to sea level (760 mm Hg) with an 80% nitrogen and 20% oxygen atmosphere; no life-support equipment will be necessary for nominal flight.
4. Acceleration will range between 2 and 4.5 $+G_z$ or G_x (depending on the space vehicle).
5. There will be different emergency egress procedures (depending on the space vehicle).

The task force also addressed other considerations, including space motion sickness, pregnancy, sudden incapacitation, and age. The final recommendations contained broad guidelines for obtaining medical histories at the time of flight application, and again immediately preflight, and the performance of a physical examination and diagnostic studies by a physician trained in aerospace medicine, the content of which depends on the information found in the medical histories.

Between 2003 and 2006, the FAA was quite active in addressing the issues of medical screening for commercial space flight crewmembers and passengers. A series of documents were prepared by the FAA culminating in a technical report "Guidance for Medical Screening of Commercial Aerospace Passengers" (9) and a Final Rule amending portions of Title 14, Chapter III of the Code of Federal Regulations, December 15, 2006 (5). The Final Rule established a medical standard requiring a current FAA second class medical certificate for crewmembers having a safety-critical role in addition to being able to demonstrate tolerance to the environmental demands of suborbital flight. However, no equivalent medical standards were established for passengers.

Philosophy behind Standards and Guidelines

Till now, all space flights for commercial passengers have been conducted on government-developed and owned vehicles. The future of commercial space flight, however, will make extensive use of commercially developed, owned, and operated vehicles. The commercial operators have a strong desire to fly as many people as is safely possible to achieve a viable and profitable business outcome. Hence, the philosophy behind the medical standards or guidelines for government organizations and commercial operators is quite different.

Table 30-1 shows a comparison of some of the differences between government programs and commercial operators. Although the goal of commercial operators is to accept as wide a group of potential passengers as possible, safety remains of paramount importance. Many factors will go into decisions regarding passenger acceptability. Issues such as operational constraints of the vehicle, acceleration (G) forces, cabin pressure, breathing gas mixture, use of pressure suits, availability of ejection seats, emergency egress requirements, presence of a flight attendant, total flight time, restriction of movement during the microgravity phase of flight, and level of risk acceptable to the passengers themselves will all be considerations in making go/no-go decisions. The need for physician specialists in aerospace medicine to provide advice on the medical suitability of passengers for suborbital and orbital space flight will continue to grow as the industry advances.

The philosophy behind standards and guidelines for crewmembers, by contrast, is much the same for government

TABLE 30-1

Differences between Government Programs and Commercial Operators

Government Programs	*Commercial Programs*
Exclusion—many disqualifying conditions	Inclusion—maximize the number of passengers
No medical mission impact	Accept limited mission impact
Limit risk of medical events	Accept some risk of medical events
Maintain safety	Maintain safety
Longer-term clearance	One-time flyers

and commercial programs. In both cases, the crewmembers may operate the vehicles multiple times over several years. The medical standards will need to address both current medical status and the likelihood of deteriorating medical conditions over the course of medical clearance. As is true for commercial aviation, reducing the risk of sudden incapacitation or performance decrements in a crewmember is of primary importance.

Informed Consent and Waivers

Although the FAA Final Rule (5) did not specify any medical standards for space flight participants, it did mandate that operators inform each space flight participant in writing about the risks of the space flight. This disclosure must include information on "each known hazard and risk that could result in a serious injury, death, disability, or total or partial loss of physical and mental function; that there are hazards that are not known; and that participation in space flight may result in death, serious injury, or total or partial loss of physical or mental function." Not specifically stated, but presumed to be included, are the risks that each participant's personal medical status contributes to the overall risk of the flight. Therefore, operators have a responsibility to conduct a medical evaluation to identify and disclose medical conditions that could have an impact on each participant's personal risk of participation.

To assist operators and space flight participants in identifying those risks, the FAA prepared a document titled "Guidance for Medical Screening of Commercial Aerospace Passengers" (9). This document divides passengers into two categories—those participating in suborbital flight with reduced G-load and those participating in orbital flight at higher G-load (and longer duration exposure to microgravity). The G level that separates the two groups is +3 Gz during any phase of the flight. In practice, this G level may place the passengers for many suborbital flights into the FAA's recommendations for the orbital passengers. In anticipation that there will be prospective passengers who have medical conditions that contraindicate participation in a space flight, the FAA recommends that operators retain specialists in aerospace medicine to evaluate these passengers on a case-by-case basis. What may result from the implementation of the informed consent approach to accepting passengers for space flight is that each operator will need to determine what methods and criteria they will use to accept or deny access to a space flight on their vehicle.

Crewmembers of commercial space vehicles, in accordance with the FAA Final Rule (5), must possess a current FAA second class airman medical certificate as well as demonstrate the ability to withstand the stresses of space flight, including high acceleration or deceleration, microgravity, and vibration, in sufficient condition to safely carry out their duties. Therefore, the medical standards and evaluation for crewmembers will need to extend beyond the FAA second class medical examination to include exposure to acceleration and deceleration in concert with the specifications of the vehicles they will be flying.

PRACTICING COMMERCIAL SPACE MEDICINE—THE FLIGHT SURGEON AS A RISK MANAGER

Because of its mission, and therefore level of risk tolerance, NASA has set strict medical standards; we see a similar set of strict standards for military and commercial aviators. However, personal space travel is still in its infancy, and is often characterized as the newest "adventure activity." So, what are the drivers for medical support of crew and passengers? Of course, the industry wants to fly as many people as possible—how can a flight surgeon support that objective? The industry also wants to optimize safety while still flying regular missions—how can a flight surgeon support this objective? Using the model of government-sponsored programs will likely result in a very restrictive definition of who may fly. Conversely, using the model of other adventure sports leads to a very different method and model for providing medical support to this nascent industry.

Although there are no definitive answers, the path to the answer is in terms of the flight surgeon acting as a risk manager. In essence this is no different an objective than the flight surgeon in the military aviation community, or in the civil federal space community. However, as we have described earlier, the criteria for success and the objectives of the personal space flight industry are different in important ways. Given these differences, what are the implications for the flight surgeon role?

Preflight

Providing medical care for commercial space flight participants will present new challenges and opportunities for the flight surgeon of the new era of space travel. The arrangements by which a physician provides services to the paying passenger are most likely to involve employment by or contractual relationships with the commercial operator. During the preflight period, the flight surgeon may be involved in medical assessment, testing/training of the passengers through centrifuge and altitude chamber exposures, possible microgravity flights, and even flights in high-performance jets. Observations made by the flight surgeon during these events will drive subsequent risk determination. The preflight analysis culminates in the flight surgeon providing recommendations to the space flight participant and the operator on the risks that need to be considered in the informed consent process.[†] Nevertheless, it is imperative that the preflight medical evaluation process ascertains the medical risks that each passenger presents, seeks ways to mitigate those risks to the maximum extent possible, and provides an accurate assessment of the risks to both the passenger and the operator so that informed consent can be given to proceed with the flight. Of course, the nature of the launch/landing vehicle (vertical or horizontal take-off and landing, etc.) and the type of flight (suborbital, orbital, etc.) are also critical factors in evaluating risk. The health observations need to be analyzed within the context of the specific mission scenario.

The use of ground-based testing and training in an altitude chamber, centrifuge, or zero G aircraft will be an especially important part of working with health-challenged passengers in preparation for a potential space flight. The personal space flight surgeon has unique opportunities and challenges specifically when working with individuals who have significant disabilities but have the means and the desire to fly in space. In appropriate simulation environments, the passenger's medical parameters can be monitored and medical intervention can be immediately accomplished, if needed. A recent example of this approach is the zero G flight of Professor Stephen Hawking who is severely debilitated with advanced amyotrophic lateral sclerosis (10). Four physicians, including an aerospace medicine specialist, were involved in supporting Professor Hawking's zero G flight. Preparation included a training flight with a healthy volunteer on the day before Professor Hawking's flight; use of equipment to monitor blood pressure, heart rate, electrocardiogram, respiratory rate, oxygen saturation, and carbon dioxide; and simulation of medical emergencies with practice of immediate intervention. With these preparations, a zero G flight dedicated to Professor Hawking was accomplished safely and without incident. Enabling individuals with severe disabilities to fly safely in space requires extensive preflight preparation and in-flight monitoring and may require a flight dedicated to such an individual with a medical support team onboard, but will open space travel to a much wider group of individuals than previously contemplated.

At this time the preflight timeline is relatively undefined across the industry; however, it is prudent to suggest that during the final 3 or 4 days of the preflight period each passenger should undergo a brief update to their medical history and an examination designed to detect acute conditions that could negatively impact the flight, such as acute infectious illnesses, exacerbations of chronic medical conditions, or upper respiratory conditions that could cause barotrauma to the ears or sinuses. The flight surgeon should also determine, based on the experience from medical history, testing, and training, whether or not prophylactic antimotion sickness medication should be recommended.

As indicated earlier, the evidence base for the exposure of the public to the environmental demands of space flight is scarce. One particularly challenging area is how to deal with passengers who are using prescription and over-the-counter medications. The effectiveness of many drugs in space will more than likely change given the effects of microgravity on various organs with an expected secondary effect on the absorption, distribution, metabolism, and elimination of drugs in the body. What is undefined is the precise nature of these changes. Given the demographic of early participants in this industry are likely to be middle aged, a large proportion will probably be using some prescription medication.

In-flight

In-flight health risk management for suborbital flights will nominally be achieved through primary preventive measures. Medical monitoring and care is likely to be very limited or even nonexistent for suborbital flights. The total duration of a suborbital flight will be in the range of 2 to 3 hours with only 4 to 5 minutes in microgravity. The vehicles will be small, and weight and power constraints will be a significant barrier to carrying medical equipment. It remains to be seen if operators will utilize a flight attendant and, if so, whether the attendant receives medical training or has the ability to provide medical assistance. Without a flight attendant, in-flight medical care will not be available under nominal circumstances. However, as mentioned in the preceding text in the context of flying disabled passengers, one might envision a scenario where a passenger wishes to pay for additional seats (or even the entire flight) to fly their physicians, other medical attendants, and condition-specific medical hardware and consumables. This may still be a problematic scenario given the dynamic flight environment, confined cabin space, and limited ability of the flight crew to alter the flight plan after the suborbital launch.

The in-flight medical capabilities for orbital flights may be more advanced. A basic medical kit could be carried on orbital flights of several hours duration with contents determined by the risk of orbital flight. Models for risk management include the addition of a medically trained flight attendant or ensuring that passengers receive training in the use of the medical kit for self-care or the care to fellow passengers.

While the suborbital and short orbital flights can focus on primary prevention and techniques for handling emergent problems, longer orbital flights of several days duration present a different set of considerations for in-flight health care that require careful analysis. These factors include exercise, nutrition, personal hygiene, chronic exposures to microgravity, environmental management, sleeping, recreation, and others. Ultimately, we will have humans flying into space to perform work and at that time, the flight surgeon will be forced to consider occupational hazards of the workplace

[†]From a medical-legal perspective, it is unclear whether these functions establish a doctor–patient relationship between the space flight participant and the flight surgeon. It may take court cases to decide this question as time goes on.

in much the same manner as on Earth. However, is it unclear who will set the standards for operation, maintenance, and protection of human health and safety on these orbital platforms. The FAA/AST does not have regulatory authority, and international Space law does not address such issues.

Postflight

Postflight medical care issues fall into two broad categories—those associated with an individual passenger's medical problems from the space flight, and those resulting from a vehicle accident. In the formative years of the industry, it will be important for the flight surgeon to maintain comprehensive records on crew and space flight participants and any observations of risk factors. This will enable any investigation to proceed more efficiently, and assist the industry in finding the root cause and fixing the problem.

Postflight medical issues for individual passengers of suborbital flights will most likely be related to resolution of vestibular symptoms or motion sickness, treatment of trauma that might have occurred during the flight, possible orthostasis, and instructions on where to obtain medical care if delayed symptoms should occur. Longer-term postflight care may be required if prophylactic medication is administered. In addition, long-duration flights will require a period of postflight rehabilitation before a full "return to duty" is permitted including driving, and certainly flying.

A final recommendation is for the flight surgeon to perform a medical debrief with all crew and passengers; this is certainly prudent in the early phase of personal flights to aid in establishing a reliable and comprehensive evidence base for continual improvement of health risk management techniques.

Crash Survivability and Emergency Evacuation

The personal space flight surgeon should be prepared for the occurrence of a space vehicle accident. Space vehicle occupants experiencing a launch or landing crash or other event requiring an emergency response will face a variety of factors that will determine their survival, and the flight surgeon needs to be familiar with both the general aspects of such an event, and the specific features of the vehicle in question. Chapter 4 provides an excellent analysis of the biomechanical effects of individual exposures to impact deceleration.

Consideration must be given to the design and use of ejection seats, space suits, and egress requirements, and in particular how these factors can change medical standards and possibly eliminate some participants. In addition, the flight surgeon will focus on four classic design concepts: (i) impact attenuation, (ii) protection of the livable occupant space, (iii) restraint, and (iv) postcrash factors including fire protection/personal protective equipment.

The use of protective equipment (crashworthy seats, seat belts, harnesses, seat belt air bags, helmets, etc.), individual positioning in preparation for an impending crash, and the crashworthy design of an aerospace vehicle will help prevent injuries and/or death during exposure to impact (see Chapter 25).

An individual who survives the impact must get out of the vehicle immediately. An occupant who is very familiar with vehicle-specific emergency evacuation procedures and equipment is more likely to escape without harm or with minor injuries only (see Chapter 25). A space flight participant who has a significant physical disability, which is severe enough to interfere with the evacuation process, may be at higher risk of experiencing injury or death in the event of a mishap. Therefore, the proper assessment of medical conditions that may interfere with an individual's ability to perform unassisted emergency evacuation procedures should be an important factor considered in the health-risk assessment of space flight participants. Furthermore, customized hands-on emergency evacuation training is highly desirable for all space flight participants.

CHALLENGES AND ISSUES

Lack of Medical Evidence

A significant challenge facing the commercial space flight industry is the lack of medical data on which to make decisions about flight risks from the medical conditions of a population of passengers with more health issues than the astronauts, cosmonauts, and taikonauts of past space flights. Although there have been career astronauts or cosmonauts who have completed space flights with significant medical conditions, the data concerning those conditions is protected by strict privacy laws and is not readily available from the governmental agencies.

However, the personal space flight industry has an opportunity to address this problem by capturing and consolidating medical data concerning crew and participants. Space flight participants of the future could help fill in the gaps of knowledge through voluntary participation in a program that managed the inclusion of their medical data in a database of all space flight participants and in medical monitoring during their flights. Because there is no regulatory requirement for such data or monitoring, acquiring medical data and performing medical monitoring will require the voluntary participation of the passengers and the support of the vehicle operators.

Assuming the technical issues could be resolved and processes for voluntary participation developed, in-flight monitoring data would be helpful to further the understanding of human physiological responses to suborbital flight in a widely divergent population. These data include heart rate, blood pressure, electrocardiogram, respiratory rate, and oxygen saturation (11). Additionally, vehicle parameters that should be monitored include acceleration, vibration, noise levels, cabin atmosphere pressure and composition, and cabin temperature. The capture of these data elements over a wide number of flights and a wide variety of passengers could greatly expand the understanding of the human response to suborbital space flight.

Medical Events and Space Flight

To date, relatively healthy individuals (professional astronauts, cosmonauts, and taikonauts) have flown in space, and, from a medical fitness point of view, they should not be considered a representative sample of the general population. However, even among these individuals who have been subject to very comprehensive initial medical selection tests and to subsequent medical screening and monitoring evaluation procedures, there are some who have experienced a variety of ground and in-flight medical events as described in Tables 30-2, 30-3, and 30-4 (Jon Clark MD, *personal communication*, 2007.)

A study of 607 astronauts and payload specialists (521 men and 86 women) involved in 106 space shuttle missions (STS-1 through STS-108) between April 1981 and December 2001 covering more than 5,496 flight days (4,673 days for men and 823 days for women) indicated that 98.1% of men and 94.2% of women reported 2,207 separate medical events or symptoms during flight (1,882 events in men and 325 events in women). Reported medical events or symptoms included space adaptation syndrome (39.6%), nervous systems and sensory organs (16.7%), digestive system (9.2%), injuries and trauma (8.8%), musculoskeletal system and connective tissue (8.2%), skin and subcutaneous tissue (8%), respiratory system (4.5%), behavioral signs and symptoms (1.8%), infectious diseases (1.3%), genitourinary system (1.5%), circulatory system (0.3%), and endocrine, nutritional, metabolic, and immunity disorders (0.1%). (Jon Clark MD, *personal communication*, 2007.) There were 194 events due to injury (including 14 fatalities).

TABLE 30-2

Reported Ground Medical Events among U.S. Astronauts

Medical Events	*Frequency*
Allergic reaction (severe)	1
Choledocholithiasis	3
Retinal detachment	2
Pancreatitis	2
Appendicitis	2
Diverticulitis	1
Ventricular tachycardia	1
Atrial fibrillation	1
Coronary artery disease	1
Hemorrhagic cyst	1
Abdominal pain	1
Duodenal ulcer	1
Inguinal hernia	4
Ureteral calculus	3
Pneumonia	2
Sudden hearing loss	2
Cervical disk herniation with impingement on spinal cord	1
Corneal ulcer	1
Malignant melanoma	1
Severe epistaxis	1
Right ovarian cyst	1
Olecranon bursitis r/o septic joint	1
Clostridium difficile infection	1
Gastroenteritis/colitis	1
Dysmenorrhea	1

TABLE 30-3

Reported In-flight Medical Events among U.S. Astronauts during the NASA/MIR Program (March 1995–June 1998)

Medical Events	*Frequency*
Musculoskeletal	7
Skin	6
Nasal congestion, irritation	4
Bruise	2
Eyes	2
Gastrointestinal	2
Hemorrhoids	1
Psychiatric	2
Headaches	1
Sleep disorders	1

TABLE 30-4

Reported In-flight Medical Events among Russian Cosmonauts during the MIR Program (February 7, 1987–February 29, 1996)

Medical Events	*Frequency*
Arrhythmia/conduction disorder	128
Superficial Injury	36
Musculoskeletal	29
Headache	24
Sleeplessness	19
Tiredness	14
Contact dermatitis	7
Conjunctivitis	6
Laryngitis	6
Asthenia	5
Erythema of face, hands	4
Acute respiratory infection	3
Surface burn, hands	3
Glossitis	3
Dry nose	2
Heartburn/gas	2
Foreign body in eye	2
Dry skin	2
Hematoma	1
Constipation	1
Eye contusion	1
Dental caries	1
Wax in ear	1

These medical considerations are very important while taking into account the increasing number of prospective commercial space flight participants who are interested in flying aboard suborbital and orbital space vehicles. Moreover, these events suggest that the provision that all commercial space vehicle operators provide full disclosure of all potential physiological and environmental risks associated with participation in space flight (suborbital and orbital) that may exacerbate underlying medical conditions is a complex endeavor. Certainly, for the early personal space flight participants, quantitatively assessing the degree of risk will entail a large degree of uncertainty.

Medical Liability and Space Law Issues

Space flight exposes individuals to an extreme operational environment that has the potential of causing discomfort, injury, or death. Therefore, the human commercial space transportation industry must be proactive in identifying the potential hazards that could compromise the health and safety of space passengers, and, at the same time, implement the necessary actions to prevent and/or mitigate such risks to protect all space vehicle occupants.

At the present time, the United States is the only country that has established civilian licensing requirements for human commercial space operations. The U.S. Commercial Space Launch Amendments Act of 2004 (4) requires space flight participants to be fully informed about all of the potential risks of participating in space flights. However, many unanswered questions remain regarding the actions that the emerging human commercial space transportation industry will have to take in order to address potential passenger liability issues.

The flight surgeon, medical organization, and the operator engaged in flying humans in space need to acknowledge and address these issues. Currently, there is no definition of the extent of the risk disclosure associated with space flight participant involvement in commercial space flights. Similarly, the content and scope of the waiver of liability to be signed by any space flight participant is unclear.

The flight surgeon will also often have to rely on the willingness of the participant to disclose current medical problems that could pose medical risks during the flight.

The flight surgeon will also be asked to advise the operator on how best to mitigate health risks. Issues of concern include the provision of some type of medical kit onboard for possible use during flight if a passenger becomes ill, and the content of such a kit. Likewise, the operator may consider providing basic life support (BLS) and cardiopulmonary resuscitation (CPR) training for space crews and/or space flight participants to be able to assist fellow occupants in case of an unexpected medical emergency during flight.

SUMMARY AND CONCLUSION

This current period in history will be known as that period when personal human space travel became a reality. It is an exciting time for human space flight in general and certainly presents some novel challenges for the space medicine community. Success, both for the industry, the fliers, and the space medicine profession, can be attained through a disciplined and principled approach to the technical, business, and human health challenges put forth in this chapter.

REFERENCES

1. *Space tourism market demand revisited*. Futron Corporation, August 24, 2006.
2. Spotts PN. *Space tourism industry is lifting off, From the X Prize to civilian trips to the moon, private space flight is attracting more interest among investors and would-be voyagers.* By Peter N. Spotts | Staff writer of The Christian Science Monitor from the July 26, 2007 edition
3. http://public.blueorigin.com/index.html.
4. *U.S. Commercial Space Launch Amendments Act of 2004 (H.R. 5382) Public Law 108–49, 108th Congress*, December 23, 2004.
5. DOT/FAA. *FAA human space flight requirements for crew and space flight participants.* Final Rule, 14 CFR Parts 401, 415, 431, 435, 440 and 460, December 15, 2006.
6. Hamilton DR, Murray JD, Kapoor D, et al. Cardiac health for astronauts: current selection standards and their limitations. *Aviat Space Environ Med* 2005;76(7):615–626.
7. Rayman RB, Antuñano MJ, Barker CO, et al. Medical guidelines for space passengers. *Aviat Space Environ Med* 2001;72(10):948–950.
8. Rayman RB, Antuñano MJ, Garber MA, et al. Medical guidelines for space passengers–II. *Aviat Space Environ Med* 2002;73(11): 1132–1134.
9. Antuñano MJ, Baisden DL, Davis J, et al. *Guidance for medical screening of commercial aerospace passengers Federal Aviation Administration*. Technical Report No. DOT-FAA-AM-06-1. Washington, DC: Office of Aerospace Medicine, 2006.
10. Mackenzie I, Viirre E, Vanderploeg JM, et al. Zero G in a patient with advanced amyotrophic lateral sclerosis. *Lancet* 2007;370(9587):566.
11. McDonald PV, Vanderploeg JM, Smart, K, et al. *AST Commercial human space flight participant biomedical data collection*. Prepared for: FAA Volpe National Transportation Systems Center Cambridge, Massachusetts, Contract DTRT57-05-D-30103. 2007.

INDEX

Note: Page numbers followed by *f* indicate figures; those followed by *t* indicate tables.

B

C

D

E

F

G

H

O

P

R

T

U

V

W

X

Y

Z