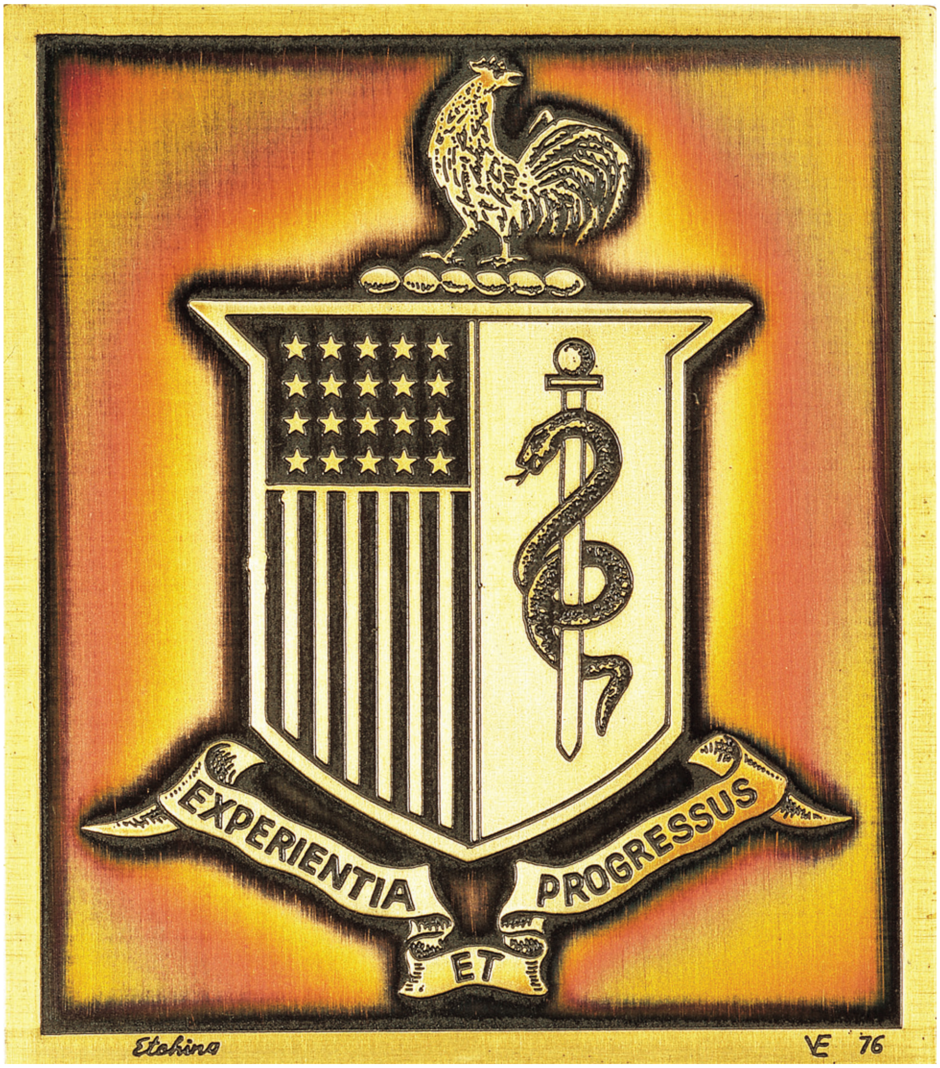
BIOMEDICAL IMPLICATIONS OF MILITARY LASER EXPOSURE



The Coat of Arms
1818
Medical Department of the Army

A 1976 etching by Vassil Ekimov of an original color print that appeared in *The Military Surgeon*, Vol XLI, No 2, 1917

Textbooks of Military Medicine

Published by the

Office of The Surgeon General
Borden Institute
US Army Medical Center of Excellence
Fort Sam Houston, Texas

Edward A. Lindeke
Colonel (Retired), MS, US Army
Director, Borden Institute

The *TMM* Series

Published Textbooks

Medical Consequences of Nuclear Warfare (1989)

Conventional Warfare: Ballistic, Blast, and Burn Injuries (1991)

Occupational Health: The Soldier and the Industrial Base (1993)

Military Dermatology (1994)

Military Psychiatry: Preparing in Peace for War (1994)

Anesthesia and Perioperative Care of the Combat Casualty (1995)

War Psychiatry (1995)

Medical Aspects of Chemical and Biological Warfare (1997)

Rehabilitation of the Injured Soldier, Volume 1 (1998)

Rehabilitation of the Injured Soldier, Volume 2 (1999)

Medical Aspects of Harsh Environments, Volume 1 (2002)

Medical Aspects of Harsh Environments, Volume 2 (2002)

Ophthalmic Care of the Combat Casualty (2003)

Military Medical Ethics, Volume 1 (2003)

Military Medical Ethics, Volume 2 (2003)

Military Preventive Medicine, Volume 1 (2003)

Military Preventive Medicine, Volume 2 (2005)

Recruit Medicine (2006)

Medical Aspects of Biological Warfare (2007)

Medical Aspects of Chemical Warfare (2008)

Care of the Combat Amputee (2009)

Combat and Operational Behavioral Health (2011)

Military Quantitative Physiology: Problems and Concepts in Military Operational Medicine (2012)

Medical Consequences of Radiological and Nuclear Weapons (2013)

Forensic and Ethical Issues in Military Behavioral Health (2014)

Combat Anesthesia: The First 24 Hours (2015)

Otolaryngology/Head and Neck Surgery Combat Casualty Care in Operation Iraqi Freedom and Operation Enduring Freedom (2015)

Medical Aspects of Biological Warfare (2018)

Military Veterinary Services (2019)

Occupational Health and the Service Member (2019)

Fundamentals of Military Medicine (2019)

Biomedical Implications of Military Laser Exposure (2020)

US Army photo

This book is dedicated to Colonel Edwin S. Beatrice, MD, who is directly responsible for much of the information and many of the ideas contained herein. Through over 2 decades of pioneering work, Colonel Beatrice laid the basis for much of the research that has since been performed to advance scientific understanding of the biomedical implications and risks associated with the use of military lasers. Although many researchers and practitioners have made important contributions to the field of laser safety, no single body of work has been more essential and notable than that of Dr Beatrice, whose career was dedicated exclusively to the study and prevention of laser-induced injury. Thus, the contributors to this Textbook of Military Medicine dedicate this volume to his work and to his memory.

BIOMEDICAL IMPLICATIONS OF MILITARY LASER EXPOSURE

Senior Editors

Bruce E. Stuck, ScD
Formerly, Detachment Director
US Army Medical Research Detachment
Walter Reed Army Institute of Research

Victoria Tepe, PhD
Senior Science Advisor
The Geneva Foundation

James W. Ness, PhD
Colonel, Medical Services Corps, US Army
Professor of Discipline and Program Director of Engineering Psychology
Department of Behavioral Sciences and Leadership, US Military Academy

Office of The Surgeon General
Borden Institute
US Army Medical Center of Excellence
Fort Sam Houston, Texas

2020

Editorial Staff: Joan Redding
Senior Production Editor

Douglas Wise
Senior Layout Editor

Vivian Mason
Volume Editor

Robert Dredden
Illustrator

This volume was prepared for military medical educational use. The focus of the information is to foster discussion that may form the basis of doctrine and policy. The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Department of the Army or the Department of Defense.

Dosage Selection:

The authors and publisher have made every effort to ensure the accuracy of dosages cited herein. However, it is the responsibility of every practitioner to consult appropriate information sources to ascertain correct dosages for each clinical situation, especially for new or unfamiliar drugs and procedures. The authors, editors, publisher, and the Department of Defense cannot be held responsible for any errors found in this book.

Use of Trade or Brand Names:

Use of trade or brand names in this publication is for illustrative purposes only and does not imply endorsement by the Department of Defense.

Neutral Language:

Unless this publication states otherwise, masculine nouns and pronouns do not refer exclusively to men.

Published by the Office of The Surgeon General
Borden Institute
US Army Medical Center of Excellence
Fort Sam Houston, Texas

Library of Congress Cataloging-in-Publication Data

Names: Stuck, Bruce E., editor. | Tepe, Victoria, editor. | Ness, James W., editor. | Borden Institute (U.S.), issuing body.
Title: Biomedical implications of military laser exposure / senior editors, Bruce E. Stuck, Victoria Tepe, James W. Ness.
Other titles: Textbooks of military medicine.
Description: Fort Sam Houston, Texas : Office of the Surgeon General, Borden Institute, US Army Medical Center of Excellence, 2020. | Series: Textbooks of military medicine | Includes bibliographical references and index. | Summary: “Lasers will continue to play an important and sometimes dangerous role on the modern battlefield. At present, there is no adequate comprehensive protection against accidental or intentional exposure to lasers in combat. Thus, it is critical that the field of laser safety research develop preventative protocols and prophylactic technologies to protect the warfighter and to support military operational objectives. This book details the current state-of-the-art in scientific, biomedical, and technical information concerning the effects of military lasers on the human body. An important purpose of this book is to identify current knowledge gaps in the various areas of this interdisciplinary field, and to offer specific recommendations for laser safety research and development into the future”-- Provided by publisher.
Identifiers: LCCN 2020008721 (print) | LCCN 2020008722 (ebook) | ISBN 9780160953798 (hardcover) | ISBN 9780160953712 (epub) | ISBN 9780160953774 (mobi) | ISBN 9780160953781 (pdf)
Subjects: MESH: Lasers--adverse effects | Eye Injuries | Military Personnel | Occupational Exposure
Classification: LCC R857.L37 (print) | LCC R857.L37 (ebook) | NLM WW 525 | DDC 610.28--dc23
LC record available at https://lccn.loc.gov/2020008721
LC ebook record available at https://lccn.loc.gov/2020008722

PRINTED IN THE UNITED STATES OF AMERICA

27, 26, 25, 24, 23, 22, 21, 20 5 4 3 2 1

Contents

Contributors

KARL E. FRIEDL, PhD
Colonel, US Army (Retired); Senior Research Scientist for Physiology, US Army Research Institute of Environmental Medicine, 10 General Greene Avenue, Natick, Massachusetts 01760

RICHARD C. HOLLINS, DPhil
Senior Fellow, Cyber and Information Systems Division, Defence Science and Technology Laboratory, Porton Down, Salisbury, SP4 0JQ, United Kingdom

JACK B. KELLER Jr
Lieutenant Colonel, US Army (Retired); formerly, Foreign Science Information Officer, US Army Medical Research Detachment-Walter Reed Army Institute of Research, 7965 Dave Erwin Drive, Brooks City-Base, Texas 78235

BRIAN J. LUND, PhD
Research Physicist, Ocular Trauma, US Army Institute of Surgical Research, 3698 Chambers Pass, Joint Base San Antonio, Fort Sam Houston, Texas 78234-7767

DAVID J. LUND, BA
Research Biophysicist (Retired), US Army Medical Research Detachment, 7965 Dave Erwin Drive, Brooks City-Base, Texas 78235

GEORGE R. MASTROIANNI, PhD
Professor Emeritus, US Air Force Academy, Colorado 80840

RUSSELL L. McCALLY, PhD
Principal Staff Physicist (Retired), Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, and Johns Hopkins University Wilmer Eye Institute, 4940 Eastern Avenue, Baltimore, Maryland 21224

JAMES W. NESS, PhD
Colonel, Medical Services Corps, US Army; Professor of Discipline and Program Director of Engineering Psychology, Department of Behavioral Sciences and Leadership, US Military Academy, 601 Cullum Road, West Point, New York 10996

JONATHAN M. NESS, BS
Chemical Engineer, Argos, Summerville, South Carolina 29486

WILLIAM P. ROACH, PhD
Chief, Physical and Biological Sciences Branch, Air Force Research Laboratory, Air Force Office of Scientific Research, 875 North Randolph Street, Arlington, Virginia 22203-1768

DAVID O. ROBBINS, PhD
Department of Psychology, Ohio Wesleyan University, 61 South Sandusky Street, Delaware, Ohio 43015

BENJAMIN A. ROCKWELL, PhD
Principal Research Physicist, Air Force Research Laboratory, 711th Human Performance Wing, Human Effectiveness Directorate, Bioeffects Division, Optical Radiation Bioeffects Branch, 4141 Petroleum Road, Joint Base San Antonio, Fort Sam Houston, Texas 78234-2644

KARL SCHULMEISTER, PhD
Consultant on Laser and Optical Radiation Safety, Seibersdorf Laboratories, Seibersdorf, Austria

PETER ALAN SMITH, PhD
Technical Fellow, Science Applications International Corporation, Tri-Service Research Laboratory, 4141 Petroleum Road, Joint Base San Antonio, Fort Sam Houston, Texas 78234

BRUCE E. STUCK, ScD
Formerly, Detachment Director, US Army Medical Research Detachment-Walter Reed Army Institute of Research, 7965 Dave Erwin Drive, Brooks City-Base, Texas 78235

VICTORIA TEPE, PhD
Senior Science Advisor, The Geneva Foundation, 917 Pacific Avenue, Tacoma, Washington 98402

JOSEPH A. ZUCLICH, PhD
Senior Scientist/Consultant, Science Applications International Corporation, 1100 Northwest Loop 410, Suite 700, San Antonio, Texas 78213

HARRY ZWICK, PhD
US Army Medical Research Detachment, Walter Reed Army Institute of Research, 3201 Sidney Brooks, Brooks Air Force Base, Texas 78235-5138; Deceased

Foreword

The number of lasers in use on the modern battlefield is rapidly growing. Worldwide, military laser systems are known to be in use by most nations. The US Department of Defense is the largest owner and user of laser systems, with applications that include range finding, communication, illumination, land mine and bomb detection and detonation, target designation, and detection of contamination. All of these laser applications are potentially hazardous to the human eye at ranges inherent to military operations. Military lasers pose other problems at much lower eye exposure energies sufficient to produce glare, dazzle, and afterimages. Depending on laser wavelength and the state of the adaptation of the eye to day or night vision, these effects may cause temporary visual decrements that can last many minutes and may interfere severely with critical tasks, such as missile guidance.

As adjuncts to other military systems, and possibly as weapons in their own right, lasers will continue to play an important and sometimes dangerous role on the modern battlefield. At present, there is no adequate comprehensive protection against accidental or intentional exposure to lasers in combat. Thus, it is critical that the field of laser safety research also advance with the development of preventative protocols and prophylactic technologies to protect service members and to support military operational objectives. Whether or not such potentially devastating weapons ever reach the battlefield, the mere threat of their use is sufficient to cause serious concern for those who perceive themselves or their comrades as vulnerable. The depth and extent of such psychological reactions are unknown as yet, but it is reasonable to be concerned about their potential impact on operational performance.

This book details what the Army has learned about the effects of military lasers on the human body. An important purpose of this book is to identify current knowledge gaps in the various areas of this inherently interdisciplinary field and to offer specific recommendations for laser safety research and development into the future. Although the militarily relevant bioeffects of lasers predominate the contributors' efforts, much of the material presented in this book is also relevant to laser–tissue interactions in nonmilitary environments.

RAYMOND S. DINGLE
Lieutenant General, U.S. Army
The Surgeon General and
Commanding General, USAMEDCOM

Washington, DC
June 2020

Preface

In 1977, an eloquent and dramatic first-hand account of laser-induced retinal injury was published in a laser journal; C. David Decker, PhD, provided the following accident victim's view:

> When the beam struck my eye, I heard a distinct popping sound, caused by a laser-induced explosion at the back of my eyeball. My vision was obscured almost immediately by streams of blood floating in the vitreous humor, and by what appeared to be particulate matter suspended in the vitreous humor. It was like viewing the world through a round fishbowl full of glycerol into which a quart of blood and handful of black pepper have been partially mixed. There was local pain within a few minutes of the accident, but it did not become excruciating. The most immediate response after such an accident is horror. As a Vietnam War veteran, I have seen several terrible scenes of human carnage, but none affected me more than viewing the world through my blood-filled eyeball. In the aftermath of the accident, I went into shock.[1(p1)]

The cardinal problem of laser safety is that of potential injury to the human eye, which is usually the result of retinal exposure to laser beams at visible and near-infrared wavelengths. The retina's delicate tissue is a very effective absorber of light at these wavelengths. The refractive media of the eye focuses collimated visible or near-infrared laser radiation to a small area, increasing its effective irradiance by more than four orders of magnitude. Because the retina is part of the central nervous system, some laser-induced lesions to the retina tend to spread and cause more widespread sensory damage. If the original lesion is located near the fovea, the resulting larger lesion may ultimately involve the fovea directly, thus reducing or eliminating acute perception of shapes and colors. The prognosis of retinal injury is further adversely affected by the fact that damaged retinal tissue cannot regenerate.

The most critical laser safety issue is that of wavelength, which determines whether the laser beam will enter the eye and to what degree it will focus on the retina. Of course, the objective of laser safety research is to define nondangerous levels of irradiation. However, this objective requires that we first be able to quantify danger to the retina, which is an exceedingly complex problem. Irradiation effects on the retina and consequent potential visual deterioration depend on a multitude of factors associated with the laser instrument itself, as well as a variety of eye-related factors. Injury severity depends on laser exposure duration, laser energy, radiant exposure (dose), irradiance (dose rate), beam divergence, and pulse repetition rate.

Eye-related factors are also important, including the size of the pupil at the time of exposure; the presence or absence of ocular media opacities (eg, cataracts); the degree of accommodation; the presence and severity of uncorrected refraction errors; the degree of absorption and reflection of the beam (which depends on the degree of retinal pigmentation); the proximity of beam exposure to the fovea; and the final lesion diameter. Although the complex influences of all factors are not yet fully understood, these factors and many others have been extensively studied for decades. Much of that knowledge is summarized in this book.

The field of laser–tissue interactions encompasses almost all branches of science, such as basic and applied physics, engineering, meteorology, biology, and medicine. Since the invention of lasers in the middle of the last century, lasers have become ubiquitous, and the study of laser bioeffects has utilized the talents and expertise of many scientists, engineers, and physicians around the world. The history of the invention and development of the laser and its multitude of applications is well known. It is a saga of almost unmitigated success in basic and applied research.

Less well known is the tremendous achievement of the research community whose work has been devoted to laser safety, especially eye safety. The eye is the body organ most sensitive to laser and other types of radiation. Countless millions of laser instruments are now in daily use around the world. Many are potentially hazardous; yet, in the decades since the laser was first invented, not more than a few hundred laser-related injuries have occurred. This extraordinary record of safety is primarily the result of dedicated and coordinated efforts to design safe applications, safety standards, prophylactic procedures, and technologies.

It is hardly surprising that critical contributions to the study of lasers and laser safety have come from within the military. Members of the armed services may be exposed to laser radiation from a variety of sources in the open field. This potential hazard is made all the more dangerous by the use of magnifying optical equipment, such as binoculars. Binoculars increase the range over which laser beams may be hazardous; nearly all of the beam energy that enters the objective lens of an optical instrument is subsequently concentrated on a very small area of the retina. This concentration increases retinal tissue damage by many orders of magnitude.

In many situations, combat personnel are compelled to look directly toward the source of the laser beam itself, making it more likely that laser exposure will occur bilaterally, in or near the fovea. The fovea is a very small (0.3. μm) but critical region of the retina that is responsible for accurate daytime and color vision. Damage to the fovea itself results in partial blindness. Furthermore, because most battlefield lasers are rapidly pulsed, casualties are likely to suffer from multiple injuries to the retina.

The US military's interest and involvement in laser bioeffects began soon after the laser was first invented in 1960. As the armed forces began to investigate and use laser instruments at wavelengths potentially injurious to the human eye, military researchers realized the need to study the extent of this new potential hazard. Many of the most notable achievements in the field of laser safety research can be traced directly to the original work of Colonel Edwin S. Beatrice, MD, and his interdisciplinary team of Army scientists, physicians, and engineers who have devoted their careers to the gathering of data necessary to formulate safety standards and procedures. Dr Beatrice's original scientific approach to determining the safety of laser beam characteristics in the 1970s was later applied to US and international standards for the safe use of all lasers.

Most successful research programs are traceable to such a dedicated visionary who has led and inspired a team of like-minded individuals to achieve new advances that could not have been predicted.

Dr Beatrice had a remarkable ability to lead by positive inspiration:

- He motivated and challenged people to action without issuing orders.
- He was able, in a seemingly effortless way, to evaluate and appreciate the unique capabilities and strengths of each individual and to reinforce and channel them toward the attainment of research goals. He did this not by command or coercion but, rather, by selfless persuasion.
- He was always ready and willing to test and adopt compelling ideas proposed by others. He did so selflessly and always gave proper credit to those who proposed their ideas to him.

These unique characteristics and abilities played a considerable role in the consistently successful efforts of Dr Beatrice's team both during and after his tenure.

Those who were privileged to know and work with Dr Beatrice also knew him as an optimistic, quick-witted, and resourceful man whose scientific and practical goals sometimes put him in creative conflict with the pace of bureaucracy. For example, in the late 1970s, Dr Beatrice was one of the first US Army investigators to introduce and use word-processing equipment to prepare his written works. He felt that it helped cut costs and save time. At that time, word processing was still a novelty, not yet welcome or understood by all. However, Dr Beatrice continued to use word processing as a tool to advance his profession, claiming that he was "processing data," which was permitted on a microcomputer.

Although Dr Beatrice's administrative persistence was essential to laboratory and program success, his greatest contributions were in science itself. Dr Beatrice was a direct participant in the work he administered, designing unprecedented experimental paradigms and solving sophisticated technical problems. His dedication to laser bioeffects research and its practical correlates was absolute and unyielding, and his lasting influence is direct in the research he performed. His ultimate impact was not only laying the groundwork for, but also establishing a model for all laser bioeffects laboratories and programs. Through the people who worked with Dr Beatrice and research that continues today, his legacy lives on. This book is a tribute to the leadership and inspiration of Colonel (Dr) Edwin S. Beatrice.

Michael Belkin, MD
Emeritus, Goldschleger Eye Institute
Tel-Aviv University, Israel

1. Decker DC. Accident victim's view. *Laser Focus*. August 1977;6:1. https://ehs.utoronto.ca/wp-content/uploads/2015/10/Laser-Accident-Victims-View.pdf. Accessed November 6, 2018.

Introduction

In 2013, the US Army terminated its military investment in laser bioeffects research because laser eye injuries were no longer perceived to be a priority medical threat. It immediately became apparent that the information produced by more than 40 years of research in this area was also rapidly fading from institutional memory—in part because the content of published and unpublished reports, as well as the experimental data forming the basis for safety standards, had not been harvested, synthesized, and organized in a summary document. Drawing on decades of military medical research not previously captured in a single work, this volume presents a synthesis of the Army's research on the biomedical effects of military laser exposure.

Initially, much of this material was drawn up under a contract from the Telemedicine and Advanced Technology Research Center at the US Army Medical Research and Materiel Command (USAMRMC) as part of an eye research program, even as access to many of the original subject matter experts who could best contribute to this knowledge base was being lost, through death or as they moved on to demanding new jobs. Several key sections stalled. After termination of the laser bioeffects research program, the need for this book became even greater, and the project was reenergized through a contract with the Military Operational Medicine Research Program (under USAMRMC), with administrative assistance from the Naval Medical Research Unit–Dayton, and with the support and assistance of the Borden Institute staff. However, some topics that should have been included for a truly comprehensive summary of the original body of work had to be abandoned, or the book might never have made it to publication.

Ultimately, the completion of this book has been through the donated time and efforts of many people, most importantly my coeditors, Colonel Jim Ness and Dr Victoria Tepe, to whom I am grateful. They have endured and persisted over a decade of effort to develop and produce this volume. Dr Tepe has been relentless in her efforts to shepherd this book to completion, including coordination of repeatedly missed deadlines with our publishers; throughout the process, Dr Tepe preserved completed work, maintained version control, and edited and reedited to get submitted manuscripts into a final format. Colonel Ness contributed steady optimistic energy, provided historical continuity, and worked tirelessly to complete new analyses, information syntheses, and updates of material in these chapters.

Dr Michael Belkin graciously provided much of the front matter for this book and originally wrote a much more detailed dedication to honor the memory of Colonel Beatrice; Belkin's first dedication captured many examples of Colonel Beatrice's management and leadership style and could have formed a chapter of its own on the topic of how to inspire and lead Army science initiatives. Finally, the editors acknowledge the expertise, dedication, and untiring efforts of Dr Karl E. Friedl for providing overarching guidance and resourcing for this project.

The editors organized this book into three logical sections: (1) background on the problem, (2) basis of the threat to performance, and (3) specialized biomedical injury studies. The first section (History and Hazards of Military Lasers) provides an essential overview of the history, development, and current use of military lasers and the documented laser accident cases and factors. Many accidental exposures can be prevented by proper use of eye protection. However, military and civilian operators sometimes opt not to wear protective eyewear because they find it impairs their ability to see critical displays and settings in high-risk settings (eg, an aircraft cockpit). Documented laser accident cases illustrate the need to consider accident factors, such as setting, laser type, and specific injury characteristics, to inform development of effective approaches to prevention, rapid diagnosis, early treatment, and pharmacologic and surgical interventions.

Vision, performance, and psychological effects of laser injury are explored in the second section, Physiological and Psychological Effects, which considers challenges related to the assessments of vision and performance, glare effects, aversion responses, and psychological and operational impact of exposure (or threat of exposure) to laser irradiation. Laser-induced damage to the central region of the eye is particularly important because the fovea is responsible for fine spatial resolution and color vision. Injury to the fovea can cause changes in visual acuity. Nevertheless, exposure to a visible laser that does not produce irreversible ocular damage can result in temporary but substantial visual impairment. These effects may be sufficient to compromise safety in high-risk environments such as aviation. Aversion responses to intense light (eg, blink reflex, pupillary constriction, and head and eye movement) may be protective, but they depend on contextual factors such as light source intensity, duration, and ambient luminance. Psychological response to laser exposure can be influenced in the short term by preexisting knowledge and beliefs and, in the long term, by postinjury treatment and subsequent knowledge gain.

Specific attributes of laser-induced thermal, photochemical, and mechanical injuries are addressed in the third and final section, Laser-Induced Injury Thresholds. Chapters in this section detail the dependence of injury thresholds upon specific characteristics of laser exposure such as wavelength, irradiance diameter, pulse repetition frequency, and exposure duration, including ultrashort lasers. Laser-induced damage to the retinal hazard region involves interactions among thermal, photochemical, and photomechanical mechanisms. Retinal injury thresholds and interaction mechanisms are also influenced by specific exposure conditions such as wavelength, exposure duration, and irradiation diameter.

Improved knowledge of these factors is important to inform laser safety and permissible exposure guidelines. Depending on exposure parameters, ultraviolet laser radiation can damage the cornea, lens, or retina. "Ultrashort" lasers can cause novel nonlinear optical phenomena, including unique retinal and skin damage. The cornea and skin are especially susceptible to painful and potentially disabling injuries by exposure to infrared radiation. This book summarizes the past generation of research and development in laser bioeffects with the intention of providing a strong foundation and inspiring the next generation of knowledge development in this area.

Bruce E. Stuck, former Director
US Army Medical Research Detachment

San Antonio, Texas
June 2019