Chapter 1

THE US ARMY MEDICAL DEPARTMENT'S ROLE AND ACCOMPLISHMENTS IN LASER DEVELOPMENT AND USE

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INTRODUCTION

> *The soldier is especially vulnerable to sustaining a laser injury. Military physicians need to increase their awareness of this potential injury and to become familiar with its manifestations. More sensitive and selective clinical tests must be devised to determine the presence of low level laser injuries which may occur before ophthalmoscopically detectable lesions develop. Military ophthalmologists have a responsibility to investigate therapeutic modalities that will offer a better prognosis and a faster recovery from laser injuries. Furthermore and equally important, we must advocate and support efforts to develop better protective eyewear to prevent these injuries.*
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> —John A. Wolfe, MD[1(p184)]

The US Army Medical Department (AMEDD) has been a longstanding partner of the Army's materiel system development efforts. The AMEDD's responsibility for system development is to ensure that hazards to soldiers who use new devices are identified and mitigated early in the development cycle. In effect, the AMEDD serves as an "independent evaluator" to assess health implications and protect the health and safety of soldiers. Shortly after the invention of the laser in 1960,[2] the Army and the AMEDD recognized the multiple potential applications of lasers to enhance the utility or performance of military systems. Typical laser emission characteristics include generation of intense beams of monochromatic optical radiation (ie, light) throughout the ultraviolet, visible, and infrared spectral regions. Laser generation facilitates the production of a highly collimated beam of light with minimal spread over distance. Nanosecond laser emissions allow accurate range and distance determinations for fire-control systems. Near-infrared "pulsed" and/or "pulse-coded" emissions allow precise, covert target designation (a missile detects the reflected pulse-coded energy from the target, which guides it to the target). Diode lasers are employed in training devices to facilitate live-fire training.

As early as 1961, the ophthalmology community recognized the potential for eye injury from lasers and began investigations.[3] Accounts of accidental eye injuries from laser radiation were published in the early to mid-1960s.[4,5] Laser wavelengths are in the visible and near-infrared spectral region (ie, the retinal hazard spectral region), and the eye, specifically the retina, is particularly susceptible to laser injury because the collimated laser energy incident on the eye and transmitted through the ocular pupil and outer ocular media is focused at a small area on the sensory retina. Early systems incorporated lasers into fire-control devices including rangefinders and designators, and these devices could produce eye trauma at tactical ranges.[6] Intense, short-pulse (nanosecond) exposures generated by early laser rangefinders and designators could produce a small retinal lesion (or "burn") at one kilometer and a retinal hemorrhage that inhibited or obscured vision at a few hundred meters.[6] Levels of laser exposure that do not cause injury (ie, laser dazzle or glare) can disrupt vision-critical performance tasks (eg, directing a TOW [tube-launched, optically tracked, wire-guided] missile during the 12 or 15 seconds of its flight; flying a helicopter at night). The potential risk increased as high-energy lasers were being developed to directly engage military materiel at tactical distances, and anti-sensor and anti-eye laser weapons with output emissions much higher than required by fire-control devices were also under development by the US military, its allies, and its adversaries.

Human Safety and Performance Limits for Military Systems

With its proactive commitment to performance and safety research concurrent with the development of new military systems, the laser biomedical research program has been the exception rather than the rule; fielding delays and retrofits have hampered many other Army technologies due to late discovery of adverse bioeffects on human operators. For example, the development of notable modern, high-powered weapons systems proceeded without consideration of blast-overpressure risks to human operators. In 1979, testing of the new M198 howitzer was stopped, and fielding could not proceed until human safety studies were conducted, because the weapon exceeded the only available biomedical standards established for noise.[7] Similarly, the most powerful shoulder-fired rocket system to date was procured with the intention that it be fired from the prone position; an after-the-fact analysis demonstrated that the reflective wave would likely injure or kill its operator.[8] Other weapons systems, such as the XM95 nonlethal munition, were delayed in testing and fielding until biomedical studies determined shoulder injury thresholds from high-recoil energy (eg, 60 ft-lb of recoil energy).[9]

Military vehicles have also been designed without full consideration to human tolerances. During World War II, the Fort Knox Armored Medical Research Laboratory focused on problems associated with hot environments and produced models of human thermoregulation for designs of tanks and future

TABLE 1-1

SIGNIFICANT ACCOMPLISHMENTS OF THE LASER BIOEFFECTS RESEARCH TEAM

Gaps	Objectives	Solutions
Research	Characterize laser bioeffects	Determined dose-response relationships for laser-induced effects in retinal, corneal, skin, and cellular models as functions of wavelength, exposure duration, and irradiance diameter (initial focus was on lasers being incorporated into systems, including ruby, neodymium, argon, carbon dioxide, and gallium arsenide).
	Determine performance consequences of glare	Characterized performance decrements from laser glare with field-relevant test outcomes directly relevant to contemporary systems such as the TOW missile (the Blaser pursuit track model).
	Provide scientific exchange	Annual conference called Lasers on the Modern Battlefield instituted a unique forum to ensure continuous validation of relevant Army research priorities and, in turn, knowledge product transition to the user community.
Safety	Guidelines for design and use of lasers	Provided biomedical data to support establishment of safety guidelines or permissible limits for laser exposure for the Army, DoD, the nation, and the world (including AR 11-9, ANSI Z136, ICNIRP, ACGIH, IEC standards and guidelines).
	International standards	Led/contributed to the establishment and updating of national and international safety standards (ANSI, ICNIRP, International Treaty on Blinding Lasers) based on findings from a planned and responsive laser bioeffects research program.
Protection	Protective equipment	Filled a major gap in soldier eye protection with development of the first combined ballistic and laser protective goggles.
	System safety	System health hazards assessment assured deployment of modern training and "smart" weapons systems with minimal or known hazards (eg, assured that the MILES live-fire simulator was safe for soldier use; provided biomedical assessments for high-energy laser program; assisted Army Public Health Command in field laser health hazard assessment program).
Clinical tools	Field diagnostics	Developed and transitioned the Aidman Vision Screener with AMEDDC&S for inclusion in the medic kit bag.
	Diagnostics	Developed metrics and imaging methods for clinical assessment of laser eye injury.
	Treatment	Established treatment protocols for laser retinal injury based on pathophysiological studies and clinical experience with steroid and nonsteroid drug treatments.

ACGIH: American Conference of Governmental Industrial Hygienists
AMEDDC&S: Army Medical Department Center and School
ANSI: American National Standards Institute
AR: Army regulation
DoD: Department of Defense
ICNIRP: International Commission on Non-Ionizing Radiation Protection
IEC: International Electrotechnical Commission
MILES: Multiple Integrated Laser Engagement System
TOW: tube-launched, optically tracked, wire-guided

vehicles.[10,11] Yet in 2004, the high-mobility multipurpose wheeled vehicle (HMMWV) had to be retrofitted with individual occupant microclimate cooling systems to extend human tolerance at ambient temperatures reaching 110°F in Iraq.[12,13]

In contrast, the Army has continuously implemented useful laser technologies with almost seamless advances, and updates of Army, national, and international laser exposure limits have been informed by a continuous flow of biomedical research findings. This acquisition model ensures that laser systems can be implemented with confidence that they enhance soldier capability and survivability while avoiding any inadvertent impairment of soldier effectiveness or unforeseen biomedical consequences.

Periodic Reinvention and Mission Reset

The Army's laser biomedical research team was forced to reinvent itself every 10 to 20 years. In a succession of three Base Realignment and Closure (BRAC) moves, the team pulled up stakes as a group and relocated, first from Frankford Arsenal in Philadelphia to the Letterman Army Institute of Research (LAIR) in San Francisco, in 1974, and then to the US Army Medical Research Detachment of the Walter Reed Army Institute of Research (USAMRD-WRAIR) in 1992, collocated with the Air Force Research Laboratory and Naval Health Research Center Detachment at Brooks Air Force Base, San Antonio. A proposed third BRAC move from San Antonio to Dayton in 2010 was reversed, and instead, a small remaining effort was consolidated within the trauma research assets of the US Army Institute of Surgical Research, Joint Base San Antonio, Fort Sam Houston.

Although disruptive, each move provided fresh local collaboration opportunities and updated research capabilities. Ultimately, continued success was supported by good technical leadership, group cohesion (involving a shared vision and zealous dedication), and an integrated and collective experience in solving biomedical problems. The multidisciplinary and collaborative team included staff members with expertise in medicine, vision research, physics and biophysics, and cellular biology. This chapter briefly recounts the history of the laser biomedical research group's key research drivers and accomplishments, as well as the group's successful "reinvention" and modernization through its successive relocations between 1968 and 2012 (Table 1-1).

FRANKFORD ARSENAL,1968–1974

Creation of the Joint Laser Safety Team

As laser applications and their potential threats began to emerge in the 1960s, the AMEDD recognized its responsibility to ensure the development of human exposure safety standards and performance thresholds for laser technology.[14–17] This required a robust database of dose-response relationships that quantified the radiation dose dependence of the biological response on wavelength, exposure duration, irradiance diameter, and pulsing characteristics.[18–24]

In 1968, the US Army Medical Research and Development Command (AMRDC) and US Army Materiel Command (AMC) Joint Laser Safety Team (JLST) was established at the Frankford Arsenal, where the first ruby laser rangefinder was being developed. The original team concept leveraged the optics, laser, and system development expertise already resident within the AMC and the medical expertise provided by the AMRDC. Location of the team at Frankford Arsenal also facilitated collaboration with other local biomedical expertise and assets located in the Philadelphia area, including the Wills Eye Hospital, Shea Eye Institute, and Franklin Institute of Science.

The goal of the team was to gain understanding of the nature and extent of laser energy effects on the anatomy, physiology, and function of the visual system. These findings would be used to establish permissible exposure limits, minimize long-term or chronic effects, specify and develop protective eyewear, characterize adverse overexposure events, and diagnose and treat laser-induced injury. The team evaluated dose-response relationships for both common and uncommon lasers available at the time, and measured both ocular and cutaneous injury threshold doses as functions of laser wavelengths, exposure durations, irradiance diameters, and pulse repetition frequencies.[25,26] Argon lasers were already used in ophthalmology clinics, but other lasers were relatively new or rare and could not be purchased commercially. To support the necessary biomedical research, optical delivery systems were interfaced with fundus cameras, and laser systems were fabricated on site[27] at the Frankford Arsenal.[26] Biological effects of ruby, neodymium, argon, carbon dioxide, erbium, and gallium arsenide diode lasers were investigated and reported.[14–17,27–30]

The AMEDD component of the JLST included military and civilian physicians, pathologists, sensory psychologists, chemists, enlisted science assistants, a veterinarian, and veterinary technicians. They were complemented by AMC civilians, including physicists, a systems engineer, electronic specialists and technicians, clerical staff, and a program facilitator who coordinated operational assistance from the arsenal's optics shop, machine shops, and fabrication facilities (Figure 1-1). The first JLST chief, Captain Maurice B. Landers, MD, was an ophthalmologist and retinal specialist; he was assisted by an AMC optical radiation physicist, deputy chief James Helfrich. The interdisciplinary military and civilian staff worked closely together in a team approach that facilitated the rapid assessment of laser health and vision bioeffects pertinent to the Army's system development and medical needs. Without the biomedical safety data supplied by the team (eg, condition-dependent dose thresholds of eye injury), laser hazard assessments would probably be more conservative than necessary and thus inhibit the testing and fielding of new, laser-based fire-control systems. The Army's laser biomedical research program[26] ensured that the United States remained ahead of peer countries in understanding the full implications of new laser technologies as they evolved.

Figure 1-1. The Joint Laser Safety Team at Frankford Arsenal, Philadelphia, Pennsylvania, circa 1973. Front row: Major R. Bruce Bedel, Helen Stanislau, Katheryn Hersch, Lieutenant Colonel Edwin S. Beatrice. Second row: Calvin Butts, D. Jack Lund, Harry Zwick, Arnold S. Brownell, Georg D. Frisch. Third row: Bruce E. Stuck, Charles Kerensky, unidentified soldier, George Raulston, Charles T. Carver, Eugene D. Carpino. Fourth row: William Zwicker, Alvin Dallas, Kenneth Bloom, Specialist Rodgers, First Lieutenant Duane Bigler, James Helfrich, Captain Steven Dixon, Specialist Freddie A. Martin.

Keys to Success: Competence, Agility, and Attention to User Needs

Mission success for the JLST derived from a simple formula that started with a good foundation in expert specialization in a new topic area that few outside of the field yet understood. Three key features of the program remained constant through its 45-year existence:

- expertise in a highly specialized topic area of unique importance to the Army,
- a semi-autonomous management process that increased agility, and
- recognized value to the user/developer community.

The work was achieved by a relatively small, dedicated team with the right mix of personnel and disciplines. As a semi-autonomous unit, it could function with agility to address research problems, characterize emerging laser technology effects, and test new hypotheses as quickly as they were identified. The team could do this without having to request permission and support for each new study through layers of administrative process. Accountability was achieved through an annual review conference (described below).

Additionally, the program could easily access new or unique capabilities to advance its research; 30% of the research, development, test, and evaluation budget resources were reserved for extramural research collaborations to augment internal projects. This yielded remarkably productive collaborations with other institutions, including the Virginia Commonwealth University, Ohio Wesleyan University, Johns Hopkins Applied Physics Laboratory and Johns Hopkins University, University of Western Ontario, University of Kentucky, Tel-Aviv University, Duke University, University of Illinois, and Massachusetts Eye and Ear Infirmary. Collaborative research projects included anatomical and electrophysiological studies on laser-exposed animals,[31–42] and addressed promising basic research themes such as electronic retinal prostheses and retinal neuroprotectant drugs.[43–49]

LETTERMAN ARMY INSTITUTE OF RESEARCH, 1974–1992

When the Frankford Arsenal's closure was pending in 1974, the AMEDD members of the JLST were moved to the newly established LAIR at the Presidio of San Francisco, California. Lieutenant Colonel Edwin S. Beatrice led the core group from Frankford Arsenal to San Francisco. When the JLST members relocated to San Francisco, they joined with the Experimental Psychology Group, who had moved from Fort Knox, Kentucky, to become the Division of Non-Ionizing Radiation in LAIR's Department of Biomedical Stress (Figure 1-2). This consolidation of Army medical research assets also brought the Army Medical

Figure 1-2. Key laser bioeffects researchers in the Division of Non-Ionizing Radiation at the Letterman Army Institute of Research, San Francisco, California, circa 1975. Pictured (left to right) are David Randolph, Bruce E. Stuck, Harry Zwick, D. Jack Lund, and Edwin S. Beatrice.

Research and Nutrition Laboratory from Denver and the Armored Medical Research Laboratory from Fort Knox under one roof with other capabilities in tropical medicine, dermatology, and surgical research.

Research Officer Talent and Leadership in Nonionizing Radiation

Uniformed ophthalmologists, pathologists, psychologists, and veterinarians made important contributions to Army laser eye research. In 1972, Major Dolph O. Adams, MD, PhD, published an article in the journal *Science*[19] reporting observations of ultrastructural changes in photoreceptors produced at low-level laser energy exposures that suggest nonthermal biological effects on the eye; this concept is still discussed today.[19,22] Many other ophthalmologists and clinical specialists contributed to the group, including Maurice B. Landers, George H. Bresnick, Edwin S. Beatrice, R. Bruce Bedell, Paul Schwaluk, Sil Biggs, Horace B. Gardner, John A. Wolfe (who introduced "Wolfe's grades"[50]), Thomas Burk, John K. Kearny Jr, Jeffrey D. Gunzenhauser, Donald A. Gagliano, Jeremiah Brown Jr, David K. Scales (an Air Force ophthalmologist on special assignment), and Henry D. Hacker. The work of these individuals and many more team members are cited in later chapters of this volume.

During the Vietnam War, individuals with bachelor's or higher degrees in the sciences were drafted as enlisted soldiers, and the team included enlisted personnel designated by their military occupational skills as physical, chemical, and biological science assistants. The team's leadership recognized their talents, encouraged their involvement in the research, and provided the mentorship and leadership needed to facilitate their contributions to the team. Many of them continued with the laser team beyond their initial term of service, and several, after completing their military enlistment, were hired as Army civilian employees and devoted part or all of their professional careers to the study of laser bioeffects. These included D. Jack Lund, Georg D. Frisch, David A. Stamper, Tom Elverson, Jerome W. Molchany, Steven T. Schuschereba, and Bruce E. Stuck. Research opportunities at LAIR's Division of Ocular Hazards, as the team was now called, were many, addressing specialties from histology to laser measurement.

The Multiple Integrated Laser Engagement System

One of the early JLST successes was its contribution to the development of a new live-fire simulator, made possible by the group's foundational research on laser eye safety limits. The Multiple Integrated Laser Engagement System (MILES), a class of gallium arsenide (GaAs) laser-based training simulators, was fielded by the Army in 1978 to assist in live-fire training of conventional weapons. With the M-16 rifle version of the MILES device, soldiers directed laser radiation at other soldiers in training for the first time. The Army leadership wanted to ensure the system was safe before its widespread use with soldiers being purposely exposed. The relocated LAIR team conducted a series of biological effect studies investigating the retinal effects of near-infrared GaAs laser radiation, the dependence of the retinal injury threshold on the retinal irradiance diameter (ie, "spot" size) from the GaAs diode, and extensive investigation and analysis of additive effects of repetitive pulses inherent to the MILES devices.[23,24,26,51–53] These studies expanded the understanding of laser bioeffects. Over the years, over 100,000 MILES devices were used in Army force-on-force training without any adverse effects.

Laser Glare, Visual Disruption, and Military Performance

In October 1980, a Los Angeles Police Department (LAPD) helicopter in flight was illuminated by an air-cooled argon ion laser in a Halloween prank. The aircrew, a pilot and copilot, were startled but maintained control; subsequently the LAPD obtained the laser used and asked LAIR to investigate the incident. The LAIR team evaluated the aircrew's eyes and vision and assessed the laser itself and the likely exposure conditions. When the laser was obtained for inspection, it was set to operate at a wavelength of 448 nm. However, there was no retinal injury as would be expected by an overexposure to that wavelength. One of the crew had a corneal abrasion, apparently due to rubbing the eye secondary to the startle experience from the laser exposure. Evaluation of the laser's emission characteristics and its distance from the helicopter indicated that the exposure was well below levels that could produce retinal injury, but even at levels below the permissible exposure limit, the laser glare appeared extremely bright and compromised the crew's ability to fly the aircraft. It became clear that laser glare, particularly under low-luminance conditions (dawn, dusk, or night), could interfere with military operations by presenting a secondary hazard. This may have been the first investigated incident of cockpit laser illumination, with risks to aviation safety that had not been previously identified.

At the time, Colonel Beatrice had repeatedly emphasized the need for a military performance metric instead of the usual laboratory tests with uncertain translation to field performance. The LAPD incident indicated a need to develop such a metric and use it to describe laser glare effects for a wide range of exposure conditions (wavelength, exposure duration, ambient luminance, etc) so that laser accident cases could be evaluated.[54–56] JLST members D. Jack Lund and David Stamper, led by Major Peter O'Mara, a research psychologist and an early Heathkit computer enthusiast, responded with the design and construction of the "Blaser," a field-relevant tracking simulator and visual performance test system.[57–60] The system consisted of a terrain board with track-mounted scale-model tanks, with angular movements adjusted to move as if the target were at 1.5 km. (The Blaser is further described in Chapter 6, and shown in Figure 6-6.)

Major Rick Levine, a pioneer in glare research work, was assigned by Colonel Beatrice to convince the members of LAIR's very cautious and conservative human use committee and the institute's commander that it would be safe to purposely expose the human eye to laser radiation. Their ultimate approval opened the door to many important laser glare-pursuit tracking studies, all conducted with no adverse effects.[58,59] The Blaser simulator provided a large body of literature on the performance impact of laser glare.[55,56] Data including time-resolved horizontal and vertical tracking error were collected and analyzed on an early Heathkit H8 computer. The LAIR investigators included Major Dave Penetar, who characterized performance effects of glare and studied the effects of chemical defense antidotes on visual function and performance metrics[61,62]; Major Elmar Schmeisser, who contributed important electrophysiology studies[37]; and Major George Mastroianni, who explored the psychological aspects of laser exposure with and without clear indication of injury and accompanying visual disfunction.[63,64]

These laser glare data were also relevant to the operation of the wire-guided TOW missile because a small disruption in tracking performance during the missile flight would result in errant missile direction and a target miss. Laboratory test results were validated in a field-based TOW missile simulator when the Army provided a modified TOW missile training system to the researchers to assess pursuit tracking deficits produced by laser glare in the field (Figures 1-3 and 1-4; see also Chapter 6, Figure 6-3). This field system was used at Camp Roberts in California to confirm or validate the laboratory terrain board results. Many studies were conducted in the Blaser laboratory simulator with soldier volunteers from the nearby 3rd Infantry Division.

Lasers on the Modern Battlefield Conference

In 1979, Lieutenant Colonel Beatrice initiated an annual research findings and critical review meeting called the Lasers on the Modern Battlefield (LMB) conference (Table 1-2). The vision for LMB was to focus on issues surrounding the development, deployment, and use of lasers by the military and provide a forum for interaction across programs and services. The LMB conference was classified, and thus limited to Department of Defense (DoD) and allied government employees covered by an official exchange agreement. The conference quickly became the DoD's annual forum to discuss laser threat intelligence and foreign science developments associated with laser technologies; development of US laser systems; military laser users' issues and concerns; laser bioeffects supporting laser safety in the laboratory and in the field; laser protection technologies for soldiers' eyes and electro-optic sensors, including protective technology developments and human factors issues (ability to perform military duties through laser protective eyewear) associated with fielding protective eyewear; and triage and treatment of laser-induced eye injuries.

Figure 1-3. Major George Mastroianni observes laser glare from a moving Bradley fighting vehicle, at a range of 1,600 m, through the TOW (tube-launched, optically tracked, wire-guided) missile tracking device modified to measure tracking error. Although the laser glare was below the exposure limit, the exposure obscured the target during bright ambient daylight, which resulted in an off-target response.

Protective Eyewear: Doing Science for the Soldier

The LMB provided an important forum to advance solutions to Army problems. In 1980, the second annual LMB conference focused on combat ocular problems; this watershed meeting led to the development of the AMEDD's first protective eyewear. The focus of the

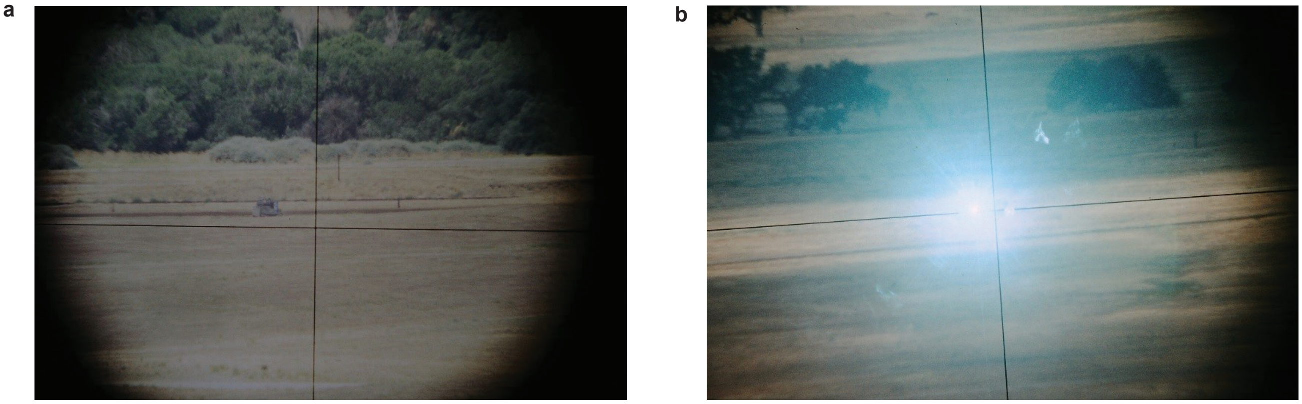

Figure 1-4. **(a)** Image of the Bradley fighting vehicle at 1,600 m through the TOW missile launcher sight. **(b)** Image through the TOW sight with a 514.5-nm laser glare from the argon laser mounted on the Bradley turret. The level of laser glare was a factor of 10 below the 10-second exposure limit of the eye; however, the target was still obscured and the user's ability to track the target was dramatically reduced.

TABLE 1-2

LASERS ON THE MODERN BATTLEFIELD CONFERENCE

Description	An annual, classified, 4- to 5-day meeting, held from 1979 to 2010, focused on the development, deployment, and use of military lasers
Purpose and scope	To enhance communications within the Army and the DoD on military laser issues
Participation	US DoD and allied governments with exchange agreements (eg, United Kingdom, Canada, Australia)
Typical topical agenda	• Plenary Briefings on Military Laser Issues • Foreign Intelligence and Threat ○ Foreign laser technology ○ Foreign military systems ○ Foreign laser threat • US Military Laser Developments ○ Laser technology ○ Military system applications ○ User concerns in military laser use • Biological Effects and Laser Hazard Assessment ○ New biological effects data pertinent to military systems ○ Exposure limits, maximum permissible exposures ○ Range safety issues • Medical Implication of Military Laser Use ○ Triage and treatment of laser-induced eye injury ○ Military and other laser exposure incidents from laser glare effects to acute injury ○ Visual function metrics and new imaging methodologies in assessment of laser-induced retinal injury • Laser Eye Protection (LEP) ○ Threat and deployed laser system-based requirements for LEP ○ Protection technologies for eyes and sensors, near term and future ○ Human factors issues associated with military LEP
Impact	• Near-term military laser issues identified in a multidiscipline environment • Early involvement of technologists, developers, and users working military laser issues • Communication of medical issues to understand the scope of hazards and threats • Reshape and/or prioritize research efforts pertinent to near-term operational issues • Facilitated safe and effective employment of military lasers

DoD: Department of Defense

conference was broader than the laser threat issue and included eye trauma from fragments, which had become common traumatic injuries in recent conflicts. Colonel Francis G. LaPiano, a prominent ophthalmic plastic and orbital surgeon, postulated that over 90% of the injuries from fragments in and around the eye that he had managed in the Vietnam War could have been prevented by a 3- to 4-mm thickness of polycarbonate (Lexan, General Electric Company).[65,66] Dr Michael Belkin made a similar argument, based on his experience as an ophthalmologist in the Israeli Defense Forces Medical Corps during the Six-Day War in 1967 and the Yom Kippur War in 1973.[67] The Army surgeon general's ophthalmology consultant, Colonel Floyd L. Wergeland Jr, agreed that fragment-protective eyewear was needed.

The human factors issues and limitations of protective solutions (absorptive dyes in glass or plastic) for laser protection were also discussed. The dyes used to provide protection against even a few selected visible wavelengths limited the overall visible light (luminous) transmission, which limited vision and distorted perception of the color space. For example, users wearing eye protection designed for ruby laser emissions at 694.3 nm were unable to readily detect red warning lights.

Furthermore, although polycarbonate provided protection against fragments, no specific Army requirement for fragment protection existed; the requirements process lagged behind the identified military medical problem and the emerging technological solutions. Although current technology programs were developing laser protection, no program addressed fragment protection as well. Absorbing dyes introduced into the polycarbonate or surface preparations to protect against lasers unfortunately degraded fragment protection properties. Polycarbonate had other drawbacks: it was "soft" and difficult to edge when formed into corrective lenses; it was very susceptible to scratches; and the lifetime of a spectacle or an aviator visor was estimated to be very short in a dusty or dirty combat environment. Another obstacle, reported by representatives from the DoD optical fabrication laboratories at Fitzsimmons, Colorado, and Yorktown, Virginia, was a lack of proper tooling to work with polycarbonate corrective lenses.

Colonel Beatrice, supported by Major General Garrison Rapmund, commanding the US Army Medical Research and Development Command, identified a clear Army need to protect soldier vision: soldiers needed functional eye protection they could use, day or night, protective against a few selected laser wavelengths and ballistic fragments. Beatrice initiated a program to develop laser radiation and fragment-protective eyewear at LAIR, and over the next 4 to 6 years, the Ballistic and Laser Protective Spectacles (BLPS) were developed.[68] The BLPS kit consisted of six elements: two toroidal polycarbonate eye wraps—one clear for use at night or under low-luminance conditions and one brown with sun protection; a laser-protective clip-on filter; side shields; silicon nose bridge pads; a corrective lens carrier for users with ametropia; and a carrying case.

The BLPS had some weaknesses. It was a "one size fits all" system, requiring an adjustable nose bridge feature. The laser protective clip-on filter was less than ideal, providing protection against just two common wavelengths used by the military, and had difficulties meeting the solarization specification. Saturation of absorbing dyes limited the protection against intense nanosecond pulses of laser radiation. To improve the system, D. Jack Lund led an effort to describe saturation measurement methods[69]; this method of testing the properties of the spectacles was written into the specification for laser protective concepts, and more recently, has been adopted by the American National Standards Institute (ANSI) in guidance for commercial laser-protective eyewear.[70] The BLPS program also produced visors for the US Army Aviation Systems Command as part of the HGU 56/P (Gentex Corporation, Zeeland, MI) helmet program. Subsequently, the BLPS system was type classified (specification for the acquisition management process that precedes procurement of an item, following provisions of Army Regulation 700-142), and some units in the Persian Gulf War were equipped with it. Some soldiers liked the BLPS system, but others did not.[71]

In 1991, a statement of work and request for proposals were issued for a follow-on program, called the "Emerging Laser Threat Eye Protection (ELTEP)." However, Major General Thomas Travis, commander of the US Army Medical Research and Development Command, canceled the ELTEP program and AMEDD's soldier eye protection programs due to mission conflict with the Program Executive Office (PEO) (Soldier). Henceforth, development of personal protective equipment ("skin out" research) would be the responsibility of PEO-Soldier, while investigation of human biomedical limits ("skin in" research) was AMEDD's mission; however, the AMEDD remained responsible for corrective lenses.

Although the BLPS system was the first fielded fragment- and laser-protective eyewear for soldiers, it never achieved overwhelming acceptance. However, the development and fielding process formed the basis for subsequent protective eye armor. Technical specifications developed for the BLPS program still guide advancements in military protective eyewear development today. These issues include level of fragment protection, solarization, saturation, scratch resistance, and numerous human factors such as operations in low-luminance environments, compatibility with other military display and lighting systems, and systems such as vehicle lighting, helmets, and optical sites.

Laser threat and hazard updates provided at the annual LMB conferences impacted military eye protection decisions in the near term and the far term. These conferences served as a forum for information exchange for all DoD eye protection development programs and identified significant human factors issues with the use of spectrally specific laser eye protection. The US Air Force and Navy managed and supported successful advanced programs that resulted in demonstrations and fabrication of advanced protective concepts, such as laser protective holograms, "dyes and dielectrics" hybrid combinations to maximize protection while preserving luminance transmittance, particle cell switches for optical sites, and graded index approaches. There is more work to be done on advanced eye protective devices, especially with new concepts to minimize or mitigate the adverse medical effects of blast, and potentially development of more effective light absorbers and diffusers.

Laser Radiation Safety Standards and Injury Evaluation Guidelines

As new cases of laser eye injury emerged, bringing demands for better protection strategies, diagnostic methods, and medical treatments, the team's research emphasis shifted from performance impairment to a more clinical focus. New technologies provided better assessment of laser injury through enhanced ophthalmic imaging diagnostics such as confocal scanning laser ophthalmoscopy (SLO) and optical coherence tomography (OCT), novel visual function assessments, and emerging molecular biological assays to complement light and electron microscopy characterizations of laser-induced eye injury.

In the late 1980s, the laser threat increased as new systems began to proliferate worldwide. The DoD developed high-energy laser systems to engage targets at long ranges. Low-energy lasers were employed in many fire-control and mission-assist applications. Predictions of laser-induced eye injuries to military personnel emerged, and laser weapons became prominent in DoD threat statements. These developments were reviewed at each LMB conference. The new threat estimates stimulated early triage and treatment investigations for laser-induced retinal injury. Pharmacological approaches were investigated.[50,72–74] The time course of injury was characterized by the assessment of stress protein release.[75–80] Emerging genomics and regenerative technologies were explored for laser-induced eye injuries.[47,81–83]

The LAIR Ocular Hazards Division assisted the AMEDD Center and School in drafting US Army Field Manual (FM) 8-50, *Prevention and Medical Management of Laser Injuries*.[84] Published in 1990, just prior to the Persian Gulf War, FM 8-50 included a unique field evaluation system to assist the combat medic in assessing acute laser eye injury: the Aidman Vision Screener (AVS),[85] a two-sided 5 × 7-inch plastic card with LogMAR and Landolt C vision acuity charts on one side and an Amsler grid on the back (Figure 1-5). The AVS was a stand-alone screening tool with instructions and a triage decision box. Although test users did not all respond favorably, AVS was eventually accepted as a vision screening tool, type classified, and furnished as required.

New potential risks also arose from the proliferation of lasers in medicine; by the early 1990s, laser use in hospitals had become common in most medical specialties. To address the new threats, including the proliferation of lasers in medicine (especially ophthalmology), industrial hygiene and occupational health guidance were established and continually updated to facilitate the safe use of lasers in the workplace. This guidance was based on exposure limits (eg, the

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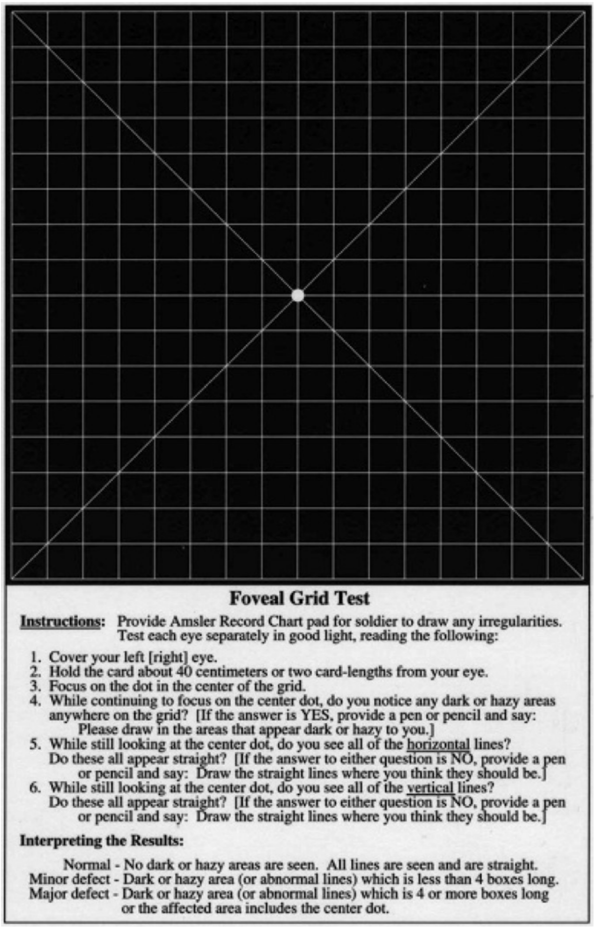


Foveal Grid Test

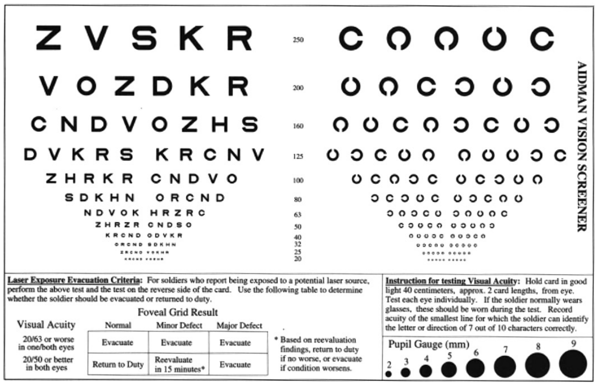
Instructions: Provide Amsler Record Chart pad for soldier to draw any irregularities. Test each eye separately in good light, reading the following:

1. Cover your left [right] eye.
2. Hold the card about 40 centimeters or two card-lengths from your eye.
3. Focus on the dot in the center of the grid.
4. While continuing to focus on the center dot, do you notice any dark or hazy areas anywhere on the grid? [If the answer is YES, provide a pen or pencil and say: Please draw in the areas that appear dark or hazy to you.]
5. While still looking at the center dot, do you see all of the horizontal lines? Do these all appear straight? [If the answer to either question is NO, provide a pen or pencil and say: Draw the straight lines where you think they should be.]
6. While still looking at the center dot, do you see all of the vertical lines? Do these all appear straight? [If the answer to either question is NO, provide a pen or pencil and say: Draw the straight lines where you think they should be.]

Interpreting the Results:

Normal - No dark or hazy areas are seen. All lines are seen and are straight.
Minor defect - Dark or hazy area (or abnormal lines) which is less than 4 boxes long.
Major defect - Dark or hazy area (or abnormal lines) which is 4 or more boxes long or the affected area includes the center dot.

b



Laser Exposure Evacuation Criteria: For soldiers who report being exposed to a potential laser source, perform the above test and the test on the reverse side of the card. Use the following table to determine whether the soldier should be evacuated or returned to duty.

	Foveal Grid Result		
Visual Acuity	Normal	Minor Defect	Major Defect
20/63 or worse in one/both eyes	Evacuate	Evacuate	Evacuate
20/50 or better in both eyes	Return to Duty	Reevaluate in 15 minutes*	Evacuate

* Based on reevaluation findings, return to duty if no worse, or evacuate if condition worsens.

Instruction for testing Visual Acuity: Hold card in good light 40 centimeters, approx. 2 card lengths, from eye. Test each eye individually. If the soldier normally wears glasses, these should be worn during the test. Record acuity of the smallest line for which the soldier can identify the letter or direction of 7 out of 10 characters correctly.

Pupil Gauge (mm)

Figure 1-5. The Aidman Vision Screener (front and back of the field diagnostic card) assists the combat medic in rapidly assessing laser-induced injury in an operational environment. It provides an Amsler grid (**a**), a visual acuity chart, and evacuation criteria (**b**). The screener is required to triage laser-induced eye injury in accordance with the guidance given in US Army Field Manual 8-50, *Prevention and Medical Management of Laser Injuries* (Washington, DC: Headquarters, Department of the Army; August 8, 1990).
Photographs: Courtesy of the US Army Medical Research Detachment.

maximum permissible exposure) for optical radiation that were based on biomedical research predominately supported by tri-service DoD research.

Over the years, the Army laser effects group maintained a close relationship with directed-energy experts at the US Army Center for Health Promotion and Preventive Medicine (USACHPPM, now the US Army Public Health Center), led by Dr David H. Sliney, who worked untiringly to draft exposure limits for laser radiation worldwide and articulate the biological effects of laser exposure and their mechanisms.[86] USACHPPM's Health Hazard Assessment Program identified urgent biomedical research requirements in support of Army laser systems and communicated these priorities to the US Army Medical Research and Materiel Command (USAMRMC) for support at the LAIR laser laboratory. Likewise, the LAIR group informed the USACHPPM of new research and research trends that impacted laser exposure limits and health hazard assessment; these interactions worked synergistically to promote the safe use of laser systems by soldiers. LAIR communications and research reports were synthesized and published in guidance on exposure limits and operational medical advice published in an Army medical technical bulletin, *Control of Hazards to Health From Laser Radiation*, in 2006.[87]

Laser Accident and Incident Registry

For the duration of their existence, the LAIR Ocular Hazards group, in cooperation with Ophthalmology Services at the Letterman Army Medical Center (LAMC), assisted in the evaluation of laser exposure incidents in the military. Emerging ocular imaging diagnostics such as SLO and OCT arrived early at the LAIR due to the pioneering work of Dr Harry Zwick in establishing the Visual Function Laboratory to assist LAMC ophthalmologists in assessment of suspected laser-induced eye injury.[54,88] In addition to advanced ocular imaging systems, nonstandard measures of visual function were used to assist diagnosis and assessment. Chromatic and achromatic threshold contrast sensitivity, color vision assessments (eg, Ishihara color plates and the Farnsworth-Munsel 100 hue test), the Amsler grid, and dynamic visual acuity metrics were used in these assessments.

In 2006, collections of data from these investigations were combined with data from the literature into a database called the "Laser Accident and Incident Registry"[89] and published as a CD ROM. The registry included clinical data and a detailed description of the operational exposure situation in each reported incident. The registry was sustained for only a few years until it was deemed not appropriate for a research, development, test, and evaluation (RDT&E) funded activity, yet no health surveillance activity was interested in continuing the effort. Nevertheless, the DoD Instruction for the DoD Laser Protection Program (DoDI 6055.15, May 4, 2007) specified the Army's responsibility for maintaining a "Laser Accident and Incident Registry" and analyzing data for use in laser safety, protection, and treatment programs for the DoD, and this directive has not been further updated. This action remains unrealized, although the Tri-Service Vision Conservation Program has retained the database in a different format.

THE USAMRD-WRAIR YEARS, 1992–2010

In September 1992, the Ocular Hazards Division moved to Brooks Air Force Base (renamed Brooks City-Base in 2002), San Antonio, to be collocated with the Air Force Research Laboratory's directed-energy bioeffects research; the Navy's nonionizing radiation programs, relocated from Pensacola, Florida, became the Naval Health Research Detachment (primarily focused on electromagnetic radiation issues). Fifty rhesus monkeys were also moved from the Presidio of San Francisco to Brooks Air Force Base. The USAMRD-WRAIR executed its mission at Brooks from 1992 through 2010. WRAIR's Department of Microwave Research was also consolidated with the USAMRD in San Antonio in 1994. Active collaborations between the two Army groups and the Air Force and Navy assets resulted in productive research initiatives addressing radiofrequency radiation hazard issues. A tri-service effort with assistance from the Johns Hopkins University produced a clear result for L-band exposure of the primate retina near the exposure limit.[90] A visiting scientist program under the National Research Council contributed work on the effects of high peak power microwaves on synaptic transmission.[91]

The USAMRMC laser bioeffects research program continued to focus on acute laser bioeffects to address gaps in the biological database required to define optical radiation exposure limits pertinent to emerging military exposure conditions. These gaps were driven by military system developments such as the use of the oxygen-iodine laser with emissions at 1.315 μm, the use of "particle cell switches" against pulsed lasers operating in the retinal hazard spectral region, and reexamination of laser glare issues surrounding the use of green laser illuminators to deter unknown encroachers on valued assets. In addition, accidental laser eye injuries continued to occur within the military, albeit at a low rate. The unit continued to help assess these exposures using advanced imaging (SLO and OCT) and measurements of visual function.[88,92] Although laser-induced eye injuries were infrequent and predominately involved the misuse of lasers in military settings, the information obtained from these and laser-induced eye injuries occurring in the private sector was important in enhancing the understanding and collection of cases from industry, medicine, and research laboratories.[93]

The emergence of the carbon suspension cell optical switch for pulse-visible and near-infrared laser exposures reopened the issue of retinal injury threshold dependence on retinal irradiance diameter. Determining the protection quality of these switches required assessment of very non-uniform retinal irradiance patterns (irradiation patterns with "hot spots"). These assessments led to biological research using the intact nonhuman primate eye to verify injury prevention efficacy and to establish measurement procedures to evaluate future suspension cell switches.[94]

Evaluation of corneal, lens, iris, and retinal injury thresholds for laser wavelengths in the 1.1 to 1.4 µm region was driven by DoD efforts to build high-energy lasers operating at the chemical oxygen-iodine laser (COIL) wavelength of 1.315 µm. Collocation of the directed-energy bioeffects research program at Brooks allowed collaboration and design of complementary research on these issues. Assisted by others in the USAMRD and the Air Force Research Laboratory's Optical Radiation Program, D. Jack Lund and Dr Joseph A. Zuclich designed and conducted a complex series of experiments addressing both the wavelength dependence and locus of ocular injury for exposures in the near-infrared spectral region, and dependence of the retinal injury threshold on retinal irradiance diameter.[95–98]

National and International Exposure Guidelines for Laser Radiation

The Brooks tri-service team published a series of papers that formed the basis for major adjustments to exposure limits that are just now being incorporated into exposure limit guidelines.[96–98] Other international collaborators made significant contributions to practical interpretations of the data for incorporating them into best practices for optical radiation hazard analysis and establishing condition-dependent maximum permissible exposures.[99] During the Brooks years, the USAMRD-WRAIR supported the DoD Joint Staff, the Army's judge advocate general, and the Department of State by providing technical advice and expertise in discussions of the "Blinding Laser Weapon Protocol" (Protocol IV of the Convention on Certain Conventional Weapons) negotiated in Vienna in 1995.

The emergence of high-powered laser diodes resulted in the proliferation of laser pointers, first red and later green. The availability of high-power laser illuminators drew attention to laser glare and purposeful exposure issues. David Stamper and Jerome Molchany continued laboratory and field studies of laser glare to assess the operational impact of non-injuring exposures.[100,101] They investigated natural protective mechanisms and described the kinetics of the pupillary response, the aversion response (consisting of head or eye movement, squint, and blink), and laser-induced afterimages from visible lasers below the exposure limits.[100,101] Major James W. Ness measured eye movements during deliberate fixations to more accurately assess the hazards of purposeful exposures.[102] Utilizing Major Ness's data, Dr Brian J. Lund developed the first retinal thermal injury model in which the source moved on the retina commensurate with the measured eye movements during deliberate fixation. With the emergence of wavefront corrected retinal imaging systems, Dr Brian J. Lund and D. Jack Lund conducted a series of experiments measuring the retinal injury threshold with wavefront correction for optical aberrations in the eye being exposed[103] (Figure 1-6). This research over a period of several years was critical to the refinement of exposure limits for optical radiation.

Figure 1-6. D. Jack Lund adjusts an optical element in one of the many optical delivery systems he developed to expose the eyes of animal models so that injury thresholds for a wide range of exposure conditions and response criteria could be measured. These data were the basis for setting safe exposure limits for humans. D. Jack Lund, in collaboration with his son, Dr Brian J. Lund (not pictured), were the first to measure retinal response thresholds with and without wave-front correction in support of the safety analysis of advanced, high-resolution retinal imaging systems.

National and international laser safety standards are important products of the Army laser safety research program. Bruce E. Stuck has been the longstanding chair, with David H. Sliney as the co-chair, of the technical subcommittee for biological effects and medical surveillance within the ANSI Accredited Standards Committee for the Safe Use of Lasers (responsible for ANSI Z136 standards). Bruce Stuck also served on the International Commission on Non-Ionizing Radiation Protection (the international standards-setting body) subcommittee on optical radiation from 1999 to 2016. Sliney and Stuck have continued to synchronize the standards for industrial hygienists and occupational health specialists through the American Conference of Governmental Industrial Hygienists Physical Standards Committee, which develops threshold limit values for optical radiation.

Diagnosis and Treatment Research for Battlefield Laser-Induced Eye Injury

Treatment of laser-induced retinal injury was addressed particularly during the Brooks years (Figure 1-7). New approaches to understanding fundamental mechanisms of photoreceptor injury and repair were developed, including refinement of animal models and a novel snake eye model.[76] Major Jeremiah Brown Jr, assisted by Lieutenant Colonel Mastroianni, led a comprehensive study of the efficacy of steroids and nonsteroidal antiinflammatory agents on thermal lesions and pulsed lesions.[48]

These built on more than a decade of basic research studies led by Dr Steven T. Schuschereba. Initial trials with corticosteroids and nonsteroidal antiinflammatory drugs were inconclusive in a rabbit model,[49,80] but further work demonstrated potent effects of corticosteroid treatment in retinal injury and highlighted the critical timing of treatments. During the early acute inflammatory phase of retinal injury, methylprednisolone worsened the inflammatory response and increased long-term scarring.[49] Neuroprotectant drugs and factors that moderated initial inflammatory responses, such as an iron scavenger (deferoxamine) and a neurotrophic factor (bFGF), protected or rescued photoreceptors from laser injury.[72]

Specific inquiries into the thresholds and timing of thermal energy damage distinguished apoptotic changes due to cell death from heat fixation, and characterized the genetic expression of heat shock proteins.[78,104] These studies suggested therapeutic targets such as heat shock protein induction by prior heat exposure and herbimycin A administration.[104,105] Novel attempts to transplant retinal cells indicated future treatment options.[47] Subsequent studies by Dr Heuy-Ching Hetty Wang investigated applications of stem cells in the treatment of retinal trauma, including novel strategies to track the fate of quantum dot-labeled stem cells transplanted into the vitreous.[81,82] Lieutenant Colonel Deborah Whitmer conducted a study investigating treatment regimens that could be initiated by first responders, followed by therapies administered later at higher medical care echelons.[83] Lieutenant Colonel Cheryl DiCarlo investigated the use of optical radiation in the treatment of laser-induced retinal injury and advanced the state of the art for using multifocal electroretinography to assess focal, laser-induced retinal injury.[77]

Contemporary treatment approaches will ultimately be based on the taxonomy of the lesion or injury. This work, along with diagnostic imaging and novel assessments of visual function, stands as the basis for future ocular trauma management. Optical radiation exposure guidelines based on DoD research findings also facilitate the development and safety of advanced ocular imaging devices.

Figure 1-7. The US Army Medical Research Detachment in front of building 176 at Brooks City-Base, San Antonio, Texas, circa 2004. Front row: Lieutenant Colonel David Scales, D. Jack Lund, Harry Zwick, Bruce E. Stuck, Steven T. Schuschereba, David A. Stamper, Jack B. Keller Jr, Captain James W. Ness. Second row: Thomas Nemeth, Fremont E. Wood, Peter R. Edsall, Ruthanne Jensen, Charles W. Van Sice, Joseph A. Zuclich, Reynaldo Broas, Sergeant First Class Stephen Hoxie, Specialist Jensen. Third row: unknown soldier, Guo Li, Michael Cross, Staff Sergeant Dan Fuller, Roosevelt Cunningham. Fourth row: Sergeant Veronica Ujimora, Sergeant First Class Sally Ruiz, Staff Sergeant Janis Loveday, Sergeant Maqsood Nawim, Claudia Wood, Jerome W. Molchany, André Akers, Roe Elliott. Fifth row: Sergeant Connie Henrichs, Specialist John Dembrowski.

DIRECTIONS FOR FUTURE RESEARCH

Treatment of laser-induced retinal injury remains a key gap research area, with the goal of minimizing the potential loss of vision induced by laser radiation for a wide range of exposure conditions inherent to military uses of directed energy.[83] While previous work has demonstrated the relative efficacy of some drugs based on the taxonomy of laser-induced injury, combined therapies and stem-cell applications will offer better treatment efficacy. Eye injuries from blasts and fragments remain a problem in current operations,[106,107] and pharmacological and surgical interventions under investigation for laser-induced retinal trauma also have applicability to eye trauma from blasts. Local administration of drugs to the eye (vs systemic administration) requires testing innovative approaches. Ocular pharmacokinetics and techniques to make both qualitative and quantitative assessments are required as enablers for treatment of ocular trauma.

The medical aspects of the full range of laser exposures, from glare to laser-induced hemorrhage, must be more fully understood. Evaluation of laser accident cases has demonstrated changes in the retina occurring over a year postinjury. Long-term follow-up of these cases should be continued. Definition of the degree and time course of visual impairment inherent to battlefield laser exposure requires additional research. With the emergence of visible laser dazzlers, the issue of long-term effects is not well understood; there is a need to characterize effects of repeated exposure in a single engagement (eg, several focal "full bleach" exposures with no ophthalmoscopically observable changes) and cumulative effects (over days or months). Advanced, rapid visual function assessment capabilities are needed to assure visual health in operational scenarios and to provide early assessment of potential functional changes from repeated or chronic exposures. Advanced diagnostic imaging of the retina (eg, OCT, SLO, and wavefront corrected retinal imaging) have great potential in assisting far-forward ocular evaluations, particularly when coupled with telemedicine. Medical research programs must be focused and sustained to provide better triage and treatment solutions for the future. Interim triage and treatment protocols must be established now. Research is needed to explore the efficacy of new drugs and drug combinations based on mechanism of injury at the molecular level, and subsequent time course and manifestation of the injury pathway.

The biological database supporting development of laser exposure guidelines must be expanded to meet the challenges posed by new military systems. With the emergence of nonlethal directed-energy systems, soldier protection must be assured by the availability of results-based directed-energy exposure guidelines. The database must also be expanded for use in specifying levels of protection required for laser eye protection systems.

Closer cooperation between medical researchers and military laser developers is needed to ensure system technology does not exceed current understanding of its biomedical implications for soldiers who may be exposed.[83] The emergence of nonlethal directed energy will require updates to testing and training policies for soldier exposure to nonionizing radiation. New technology must be employed to assess radiation bioeffects, to understand injury mechanisms, and to determine the efficacy of treatment regimes. As research in the use of these technologies matures, the results must be integrated in military medical doctrine and practice.

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