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MAJOR REVIEW

Laser Eye Injuries

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Abstract. Laser instruments are used in many spheres of human activity, including medicine, industry, laboratory research, entertainment, and, notably, the military. This widespread use of lasers has resulted in many accidental injuries. Injuries are almost always retinal, because of the concentration of visible and near-infrared radiation on the retina. The retina is therefore the body tissue most vulnerable to laser radiation. The nature and severity of this type of retinal injury is determined by multiple laser-related and eye-related factors, the most important being the duration and amount of energy delivered and the retinal location of the lesion. The clinical course of significant retinal laser injuries is characterized by sudden loss of vision, often followed by marked improvement over a few weeks, and occasionally severe late complications. Medical and surgical treatment is limited. Laser devices hazardous to the human eye are currently in widespread use by armed forces. Furthermore, lasers may be employed specifically for visual incapacitation on future battlefields. Adherence to safety practices effectively prevents accidental laser-induced ocular injuries. However, there is no practical way to prevent injuries that are maliciously inflicted, as expected from laser weapons. (**Surv Ophthalmol 44**:459–478, 2000. © 2000 by Elsevier Science Inc. All rights reserved.)

Key words. laser-induced eye injury • laser weapons • military weapons • occupational laser injury • retinal laser injury

The first laser was produced in 1960.[124] It was soon tested on animal eyes[195] and then used to produce therapeutic photocoagulation and treat eye diseases in humans.[46,198] At the same time, uses for lasers were found in other fields of medicine, as well as in science and industry, and the first reports of accidental laser eye injuries followed.[53,100,150] There are now well over 100 reports of laser eye injuries in the medical literature, enabling the characterization of this type of condition.

Today, laser-based devices are widely used by armed forces for such tasks as range finding and guiding "smart" weapons to their targets. This has led to military-related laser eye injuries.[21,44,74,87,104,117,125,139,168,174,175] In recent years, a new class of weapons has emerged, in which the laser beam is used to damage electro-optical sensors. Most of these sensors operate in and are vulnerable to the visible and near-infrared (IR) part of the electromagnetic spectrum, which is also the part of the spectrum that is concentrated on the retina. This raises a new threat of visual incapacitation of potentially catastrophic proportions in terms of the severity of injuries and the number of casualties, should these weapons be used against personnel in the battlefield. In this review, we outline basic concepts concerning the interaction of eyes and laser beams, describe the clinical aspects of laser eye injuries and the meager treatment available, and characterize the threat of military laser weapons.

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I. Physical and Pathophysiologic Basis of Laser Eye Injuries

A. LASERS AND VULNERABILITY OF THE EYE TO LASER RADIATION

The term *laser* is an acronym for *light amplification by stimulated emission of radiation.* A laser device produces a light beam that, unlike ordinary light, is coherent, monochromatic, unidirectional, and minimally divergent. Consequently, such a device can direct most of its radiant power over very small areas, even at great distances. Light radiation in the visible and near-IR part of the electromagnetic spectrum is gathered and focused by the refractive media of the eye to a retinal image about 5 to 30 μm in diameter.[33] This focusing increases the retinal irradiance (energy per time unit per unit area) by a factor of well over 10,000 above the irradiance incident at the cornea. With the use of binoculars or other magnifying optics, which further collect incoming light, the increase in irradiance may reach more than a millionfold. Since no other body organ focuses light radiation in this way, the retina is the tissue most vulnerable to laser injury. Another consequence of this concentration of energy is that even small amounts of energy produced by relatively low-power laser devices can significantly damage the retina. Such lasers are commonly used in laboratories and the military, and they emit energy in the order of tens of millijoules (pulsed lasers) or hundreds of milliwatts (continuous-wave lasers). Since higher-energy lasers are less commonly used, accidental injury of external eye structures or skin is rare. For these reasons, this review will mainly address laser injuries of the retina.

B. DETERMINANTS OF LASER-EYE INTERACTION

1. Laser-Related Factors

An important determinant of damage is the wavelength of the radiation. Optical radiation (visible and near-IR, between 380 and 1,400 nm) is transmitted by the optical media of the eye[38,79] and focused on the retina, which may be damaged by radiation doses at or above a certain threshold value. Photons of shorter wavelengths (ultraviolet [UV]) are rapidly absorbed by organic molecules in tissues and may cause corneal injury via a photochemical process.[109,125,196] Longer wavelengths, such as those of the far-IR CO_2 laser, are rapidly absorbed by water in any tissue, do not penetrate deeper than 100 μm into the cornea, and may produce corneal injury by a thermal process.[67,125,145,186] At sufficiently high energy levels, corneal perforation occurs.[66]

Two other interrelated factors determining the damage mechanism and, hence, the extent of the injury are the pulse duration and the energy level of the beam. Basic terms are defined in Table 1. With regard to pulse duration, a laser may be operated in one of several ways.[146,186] One mode of operation is the continuous-wave mode, in which the laser emits radiation continuously over time. A shutter can control the output in order to produce discrete "pulses," typically lasting milliseconds to seconds. Lasers operated in this mode include the argon and krypton photocoagulators and the surgical CO_2 laser. When a laser is operated in a "Q-switched" mode, its output consists of very short pulses of very high energy. The pulse duration is few to tens of nanoseconds. A typical laser of this type is the Nd:YAG photodisruptor. A similar mode of operation is the mode-locked type, which produces a series of very short pulses, on the order of picoseconds.[167] The Q-switched and mode-locked lasers typically produce very high power concentrations and are, therefore, more dangerous over long distances (if the beam remains collimated).

Obviously, more energy will produce more damage. In general, the same amount of damage can be produced by less energy when the energy is delivered in shorter pulses.[37,108,187] Energy and pulse duration determine the damage mechanism—thermal, mechanical, or photochemical. Thermal damage occurs when enough energy is absorbed by a suitable chromophore (a pigment with a color that absorbs the laser's particular wavelength) at a pulse ranging from microseconds to seconds, producing heat faster than it can be dissipated. Tissue temperature is thus increased.[67,131,135,149] Since the amounts of light absorption and temperature increase are proportional to radiant exposure, these processes are described as "linear." An increase in temperature of at least 10°C[125,126,149] causes denaturation and coagulation of proteins, resulting in cell death, with ensuing tissue necrosis and scarring. In this way a lesion is produced. Thermal damage is produced clinically by laser "photocoagulators," such as argon and krypton.

The most important pigment determining absorption by and, hence, thermal damage to the retina is melanin, which absorbs light throughout the visible

TABLE 1

Basic Terms Used to Describe Laser Systems

Energy	The capacity for doing work, measured in joules (J). Energy is commonly used to express the output of pulsed lasers, such as Nd:YAG.
Power	The rate of energy delivery, expressed in watts (W) (joules per second). Power is used to express the output of continuous-wave lasers, such as argon.
Irradiance	Radiant power per unit area incident upon a given surface, such as the retina, measured in watts per unit area (e.g., W/cm^2).

and near-IR spectrum[86,130,131,186] and is densely concentrated in the retinal pigment epithelial (RPE) cells and focally in the choroid. It is in this area that the thermal damage is greatest. Xanthophyll, visual pigment, and hemoglobin are present in small quantities and absorb light at more specific wavelengths than melanin. These pigments contribute little to the increase in temperature, unless they are irradiated by a laser whose energy is specifically absorbed by them. Examples of clinical consideration of these pigments include use of the dye yellow laser wavelength (577 nm), best absorbed by hemoglobin, for coagulating retinal vascular lesions, and the avoidance of argon blue laser light (488 nm), best absorbed by xantophyll, when photocoagulating in the macula.

Mechanical damage is caused when energy is absorbed rapidly at a pulse duration of picoseconds to nanoseconds, like that of the Nd:YAG photodisruptor. The energy is deposited in the tissue so rapidly that cooling resulting from heat dissipation cannot take place. A very rapid increase in temperature results (thousands of degrees), with stripping of electrons from atoms and disintegration of a small volume of tissue into a collection of ions and electrons called plasma.[86,126,130,131] This is a nonlinear process that occurs only above a certain ("optical breakdown") threshold of irradiance and is difficult to predict. In combination with the ensuing vaporization of water, it generates a compressive pressure pulse (explosion), which travels out from the site of exposure at the speed of sound and disrupts the surrounding tissues. This process is employed clinically by laser photodisruptors for procedures such as iridotomy. Moreover, since it is not significantly dependent on tissue pigmentation,[130] it can also be used for disruption of the opacified posterior lens capsule and vitreal bands. In the retina, such a pulse may cause severe damage, including retinal perforation. At higher energies there is disruption of choroidal blood vessels with subretinal hemorrhage, and at even higher energies vitreous hemorrhage results.

Photochemical processes occur when laser energy is delivered at relatively low power and long pulses, more than a few seconds. The slow delivery of energy does not cause significant buildup of heat.[90] Rather, single photons induce chemical reactions in absorbing molecules. At shorter wavelengths, i.e., in the UV range, each photon is highly energetic and can directly break molecular bonds in nucleic acids and structural proteins.[93] Photoreceptor cells damaged in this way may recover within weeks, but above a certain threshold, cell death gradually follows.[130] This process is utilized by excimer lasers in refractive surgery, where the objective is to precisely reshape the cornea without having appreciable thermal effects on tissues surrounding the incision.[183] Retinal photic injury from operating microscopes occurs by a similar mechanism.

Other beam-related factors that influence the ocular damage include beam divergence, spatial distribution of the energy within the beam, pulse repetition rate, and atmospheric phenomena. A laser beam does spread, and some systems are designed to produce a beam more than a meter in diameter, with consequent decrease in energy density. A repetitively pulsed laser may produce more than one lesion in the same eye. A laser beam may be attenuated and dispersed by the atmosphere, depending on water content and pollution.

2. Eye-Related Factors

The single most important factor in determining the degree and likely persistence of functional ocular damage is the retinal location of the laser injury or, more specifically, its proximity to the fovea. A suprathreshold lesion in the fovea will reduce visual acuity immediately and significantly in proportion to the number of photoreceptor cells destroyed. Parafoveal lesions might involve the fovea temporarily through edema and inflammation, which can extend over a diameter several times that of the injury spot.[187] These, however, subside naturally over days or weeks.[21,28,29,72,94] A parafoveal lesion might also spread to involve the fovea through the process of secondary neural cell damage, as discussed below. This secondary process may lead to permanent foveal damage and, hence, functional loss.

Retinal burns further away from the fovea will not result in appreciable or permanent functional damage; the local scotoma produced usually goes unnoticed and may be completely asymptomatic.[21,39,74,193] However, a more energetic injury will cause intraocular hemorrhage and, thus, may affect vision, irrespective of its location. If the energy is high enough, a lesion may also cause damage to the nerve fiber layer and, thus, produce a scotoma many times the size of the lesion, extending from the lesion peripherally.[199] Such a scotoma is usually permanent and may be of considerable functional importance, especially if the lesion is in the papillomacular bundle; this has been described after both accidental laser injury[21,59,174] and clinical peripapillary photocoagulation.[83,176,185]

Like any bright light, visible laser exposure in the macula activates the blink reflex, another major eye factor, and, thus, the duration of exposure is restricted to about 0.15 to 0.25 sec. Together with turning away of the head, this "aversion response" may provide an important natural defense against relatively low-power, long-pulsed lasers. It is not effective, however, against devices that produce very short pulses and fire at a high rate,[104] nor does it limit the exposure to invisible radiation. Quite differently, an initial exposure in the retinal periphery might cause an instinctive turning of the head toward the light source and, thus, lead to macular injury.[39,104,129]

Additional relevant parameters include pupil diameter. If the pupil is dilated, more energy incident at the cornea will enter the eye, and a laser lesion occurring at night or under other dark conditions will, therefore, be more severe than in daylight. A heavily pigmented retina and choroid will absorb more of the laser energy, and thus a dark-skinned individual is likely to suffer more severe injury than a light-skinned one.[47]

Interestingly, the state of refraction of the eye at the moment of laser injury will affect the outcome, as in ametropia the beam will focus in front of or behind the retina and spread on a larger retinal "blur circle," with a corresponding decrease in energy density.[31,94,101,164] A reduction of eye dioptric power of 1 D leads to a 10-fold increase in retinal spot size, while irradiance is decreased by two orders of magnitude.

C. ENERGY THRESHOLDS FOR LASER EYE EFFECTS

1. Retina

Many studies have documented the energy required to produce retinal damage (Table 2). Most of them report the minimal, or threshold energy required to produce an ophthalmoscopically detectable lesion, typically a small, gray-white spot (Fig. 1). The threshold value is usually recorded as the ED50 for the total energy entering the eye, i.e., the energy level that will produce the lesion in 50% of cases. These values, with additional safety factors and extrapolations, form the basis for laser safety practices and standards by specifying the "maximum permissible exposure" (MPE) levels to which a human can be exposed without incurring injury.[11,129] Other studies have reported energy correlates for suprathreshold injuries that lead to retinal hemorrhage, and for the so-called subthreshold injuries observable only by methods that are more sensitive than ophthalmoscopy, such as retinal histopathology and fluorescein angiography.

a. Pulsed Laser Threshold Lesions

In early studies on pigmented rabbits,[47,108] a ruby laser (694.3 nm) was found to produce detectable retinal spot lesions by delivering 270 μJ in a 0.7-ms pulse, 80 μJ in a 0.5-ms pulse, or 2.2 μJ in an 80-ns pulse. Campbell et al additionally reported higher ruby laser threshold values in the maculae of two human eyes (with a clinical diagnosis of malignant melanoma) of 1,110 μJ in a 0.7-ms pulse, with even higher thresholds in other areas of the posterior pole and in the eye with less pigmented fundus and mild cataract.[47] In another study of five eyeballs in living subjects, the retinal threshold was 1,550 μJ for a 150-μs pulse from an Nd:YAG laser (1,064 nm).[152] In that study, threshold values were found to be lower by a factor of 3.4 in rabbits and by a factor of 6 in rhesus monkeys.

Fig. 1. A series of threshold argon laser lesions in a rhesus monkey eye.

Vassiliadis et al reported in 1970 the observed threshold values for rhesus monkeys and human volunteers. Human retinal damage was observed at pulses of 68 μJ/20 ns and 950 μJ/ 200 μs for ruby laser.[187] Thresholds for monkey eyes were lower by a factor of up to 20.

Goldman et al reported thresholds of less than 20 μJ using "ultrashort" 30-picosecond (ps) pulses of Nd:YAG laser on rhesus monkeys.[85,86] Light- and electron-microscopic sections taken 1 hour after exposure showed that the focus of damage was in the RPE cells, where melanin granules were disoriented, scattered, and ruptured, and portions of RPE had separated from Bruch's membrane. Photoreceptor outer segments showed some disorder in the packing of the disks, and inner segments were vacuolated with both swollen and shrunken mitochondria. The outer nuclear layer contained pyknotic nuclei.[132] These observations are consistent with a mechanical-explosive mechanism of damage.

Cain et al used an Nd:YAG pumped dye laser to produce pulses as short as 90 femtoseconds (fs) on rhesus monkey eyes.[45] The ED50 for visible retinal lesions after 24 hours at a pulse duration of 600 fs was 0.26 μJ (λ = 580 nm). The ED50 for 4-ns pulses was 0.9 μJ (λ = 532 nm). Toth et al showed that subnanosecond pulses caused small foci of retinal pigment epithelium and retinal disruption, without

TABLE 2

Representative Energies Required to Produce Retinal Lesions by Pulsed Lasers

Species	Laser	Pulse Duration	Energy	Effect	Reference
Rabbits	Ruby	500 μs	80 μJ	Threshold lesion	108
		80 ns	2.2 μJ	Threshold lesion	
Humans	Ruby	700 μs	1,110 μJ	Threshold lesion	47
Rabbits		700 μs	270 μJ		
Humans	Nd:YAG	150 μs	1,550 μJ	Threshold lesion	152
Rabbits			885 μJ	Threshold lesion	
Rhesus monkeys			259 μJ	Threshold lesion	
Humans	Ruby	200 μs	950 μJ	Threshold lesion	187
		20 ns	68 μJ	Threshold lesion	
Rhesus monkeys	Ruby	200 μs	80 μJ	Threshold lesion	
		10 ns	22 μJ	Threshold lesion	
Rhesus monkeys	Nd:YAG	30 ps	13 μJ	Threshold lesion	86
Rhesus monkeys	Dye	4 ns (532 nm)	0.9 μJ	Threshold lesion	45
		600 fs (580 nm)	0.26 μJ	Threshold lesion	
Rhesus monkeys	Nd:YAG	30 ns	1,700 μJ	Subretinal hemorrhage	37
			2,300 μJ	Vitreous hemorrhage	
Rhesus monkeys	Frequency-doubled Nd:YAG	20 ns	156 μJ	Vitreous hemorrhage	80

choriocapillaris involvement, even with full-thickness retinal injury.[62,182]

b. Pulsed Laser Suprathreshold Lesions

The energy requirements for suprathreshold injuries, namely periretinal and vitreal hemorrhages (Fig. 2), were determined in rhesus monkey eyes by Blankenstein et al, who used an Nd:YAG laser with a 30-ns pulse duration. Retinas were viewed immediately after exposure.[37] The ED50 at the macula was 1.7 mJ for subretinal hemorrhage. Histologic examination showed penetration of the RPE and Bruch's membrane by choroidal blood, causing retinal detachment, with some changes in the outer nuclear and outer plexiform layers. The ED50 at the macula was 2.3 mJ for vitreous hemorrhage. Histology showed a portal through the disrupted neural retina, through which choroidal hemorrhage entered the vitreous chamber. Higher ED50 values were observed for extramacular hemorrhages. The mechanism of injury was presumed to be a combination of mechanical and thermal.

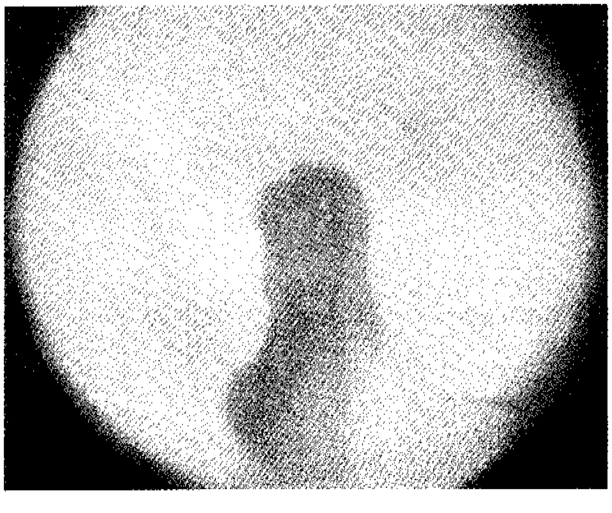

Fig. 2. Vitreous hemorrhage induced by an Nd:YAG (1,064 nm) Q-switched laser in a rhesus monkey eye (courtesy of the Medical Research Detachment, Walter Reed Army Institute of Research, San Antonio, Texas).

In two other studies in rhesus monkeys,[80,197] which used shorter wavelengths (440, 530, 694 nm) with pulses of 5 to 20 ns, retinal hemorrhage was found to occur at lower thresholds of 156 to 280 μJ. Here, too, the hemorrhage appeared immediately after exposure, and macular thresholds were lower than those of peripheral retina. Thresholds for a long-pulsed injury (70 μs) were found to be more than 100 times higher.

Toth et al examined the effect of subnanosecond pulses of visible laser on *Macaca mulatta* monkeys. At pulses ranging from 90 fs to 60 ps, less than 7 μJ caused disruption of RPE and retina with intraretinal hemorrhage from retinal vessels with no involvement of the choriocapillaris.[182]

Manning et al used a Q-switched Nd:YAG laser to deliver pulses of 6 to 10 mJ to a 30-μm retinal spot on a human patient's eye before it was exenterated because of squamous cell carcinoma of the orbit.[128] All laser applications created choroidal hemorrhages of severity directly proportional to the energy used. Histologic examination of the lesion showed disruption of all retinal layers, absence of RPE, and breaks in Bruch's membrane through which fibroblasts were seen entering from the choroid into the subretinal space. At the periphery, pigment-laden macrophages were observed, with serous elevation of the retina peripheral to them. Interestingly, Jampol et al[101] reported that when similar Q-switched Nd:YAG pulses of 6–8 mJ were focused 2–3 mm in front of the retina, only delayed and minor RPE effects were observed, together with microperforation of a retinal vein.

In summary, short-pulsed lasers, which are currently in widespread use, may cause a human retinal lesion at a minute energy of a few microjoules, and a retinal hole with vitreous hemmorhage at a few millijoules or less (Table 1). Generally, shorter pulse durations are associated with decreasing damage thresholds, and these will continue to shorten as technology advances. In the above-mentioned experiments, more energy was consistently needed to produce retinal lesions in humans than in monkeys or rabbits. This can be partially explained by interspecies differences in retinal pigmentation and light transmission and absorption by ocular tissues. In equal experimental settings, higher thresholds were reported for immediately observed lesions than for lesions observed after 1 to 48 hours. Reactive inflammation, which develops during this interval, clearly makes the lesion easier to detect. Higher thresholds were reported for the Nd:YAG laser than for visible light lasers, probably because of the higher transmission and absorption of the eye at the visible spectrum.[79,146] The repeated observation of lower burn thresholds at the macula than at the peripheral retina may be explained by the thicker macular pigment epithelium, which can absorb more radiation.[65] The lower macular threshold for vitreous hemorrhage may be explained, in addition, by the thinner neural retina and internal limiting membrane, which offer less resistance to intraretinal blood.

c. Continuous-Wave Laser Threshold Lesions

Threshold studies have been conducted with use of continuous-wave lasers, which produce longer pulses, on the order of milliseconds. L'Esperance and Kelly described in 1969 the effects of argon laser on rhesus monkey retina.[113] To produce a threshold lesion, a longer exposure required more total energy entering the eye, but less corneal power. At 2 ms, 74 mW (140 μJ) produced a lesion, while at 20 ms, a power of 36 mW (720 μJ) was required. A krypton laser operating at 586.2 nm was shown by Dunsky and Lappin to produce a threshold retinal injury at a power of 22.5 mW for 33 ms and at 25 mW for 16 ms.[61] Similar results were reported by Ham et al, who observed, in addition, lower power thresholds at longer exposure times; at 1 second, the power needed was less than 10 mW.[89] Histologic sections of threshold lesions again demonstrated that the most extensive pathology was restricted to the RPE layer and adjacent receptor cells. Features included disruption of RPE cells, dispersion of pigment granules, pyknosis of nuclei and protein coagulation within the receptor cell layer, and edema of the outer plexiform layer involving an area about three times greater than the area of RPE damage. The authors calculated a power threshold for thermal retinal damage of 7 mW entering the cornea (with dilated pupils), below which a steady state is presumably reached, in which the entry and dissipation of energy are equal and, thus, retinal temperature is not critically increased.

In clinical practice, retinal photocoagulation is generally achieved with use of power of hundreds of milliwatts and exposures of 0.05 to 0.5 second, with laser settings individually tailored to achieve a desired appearance of the lesion.[112] Histopathologic findings similar to those observed in animal models have been described.[188]

d. Subthreshold Laser Effects

Subthreshold exposure to laser light has been shown to cause structural damage to the eye, as detected by methods such as electron microscopy and fluorescein angiography.[20,40] In another investigation, however, fluorescein angiography was found to be less sensitive than fundus photography in detecting threshold lesions.[45]

Lower radiant exposure may cause only biochemical perturbations, albeit with significant functional consequences.[32,154] The effects of such subthreshold exposures were recently measured with use of models of visual performance. Robbins et al exposed awake, task-oriented rhesus monkeys to Q-switched laser irradiation at levels where no tissue damage or edema was expected.[153] A definite decrease in visual acuity could be observed after single or multiple pulses aimed at the fovea, without permanent deficit.

In a series of studies, Stamper et al evaluated the pursuit tracking performance of human volunteers during exposure to visible laser light of irradiance levels below the MPE levels provided in the ANSI-Z 136.1 standards (up to 0.4 MPE).[172,173] Significant deficits were detected in the magnitude and duration of off-target excursions. Despite these transient disruptions in performance, after more than 1,500 exposures there was no change in visual performance or fundus appearance.

These studies demonstrate the phenomenon of glare, which is a reduction or total loss of target visibility caused by a nearby source of bright visible light. It results from light scatter by the atmosphere and ocular media, which floods the retina with visual stimuli and lasts only as long as the light is actually present in the individual's field of view.

Another subthreshold phenomenon is flashblindness, which is the temporary inability to detect or resolve a visual target after exposure to any bright light. It is caused by a temporary depletion of visual pigment and, perhaps more importantly, overloading of neural circuits along the visual pathway. It lasts for seconds to minutes. Following flashblindness, afterimages may persist for minutes, hours, or even days.

Any appreciable light exposure under a night vision situation will cause a loss of dark adaptation for up to half an hour.[151]

Temporary visual impairment may be dangerous during vision-critical activities, such as driving, or in military situations, for example, where an air crew may be rendered incapable of accomplishing its mission or even of navigating the plane. Significantly, such impairment may be produced rather easily, for example, by laser pointers that have become increasingly common, even to the point of being promoted and used as children's toys.

2. Cornea

Threshold levels for corneal damage have been studied, mainly with use of the continuous-wave carbon dioxide laser. This laser operates at a wavelength of 10,600 nm, to which ocular tissues are opaque; that is, they have high absorption, and are therefore prone to considerable damage.

Fine et al were the first to describe the effect on rabbit corneas of CO_2 laser exposures of 1-second duration and variable power. An intense white opacity was produced by 3 W (3 J, 15 W/cm21).[66] With more power, both charring and ulceration were observed, and perforation occurred at 10 W. The depth of penetration into the cornea appeared to be roughly proportional to the power density of the irradiation. The authors reported histologic and electron-microscopic changes similar to those obtained when experimental nonlaser thermal burns were produced on the rabbit cornea. They concluded that the damage was caused by heat-induced chemical and morphologic alteration of collagen fibrils and ground substance material. In nonpenetrated eyes, there was no evidence of deep intraocular damage, except lens concavity, presumably caused by heat transmission. The authors further reported that transscleral irradiation at 20 W resulted in penetration of the globe, with vitreous loss and retinal tears.

Fine et al subsequently reported damage thresholds for rabbit corneal damage by CO_2 laser.[67] Irradiation at a power density of 0.1 W/cm^2 was found to be noninjurious, even at long exposures (up to 30 minutes), according to clinical and histopathologic examinations. When the power was gradually increased from 0.15 to 1.0 W/cm^2, epithelial and then superficial stromal changes could be detected both histologically and clinically. As the intensity increased, the required exposure duration shortened from 30 minutes to less than 5 minutes.

Peppers et al examined rabbit corneal damage thresholds for short exposure times.[145] They found ED50 values of 22 W/cm^2 (1.2 J/cm^2), 77 W/cm^2 (0.77 J/cm^2), and 157 W/cm^2 (0.55 J/cm^2) for exposures of 55 ms, 10 ms, and 3.5 ms, respectively.

Borland et al reported somewhat lower thresholds for 70-ms pulses.[41] The ED50 values were 5.8 W/cm^2 for minimally visible corneal opacification, 9.7 W/cm^2 for reversible epithelial loss, and 17.4 W/cm^2 for stromal coagulation and scarring.

II. Clinical Aspects of Laser Accidents

The vulnerability of the eye to laser radiation has resulted in a significant number of accidents, reported and unreported, in laboratories, industry, therapeutic procedures and military circumstances. Initially, not all civilian inuries were reported in the literature because of restrictions in connection with legal proceedings,[154,192] and reports of military injuries were often restricted by secrecy. Today, laser accidents are seldom reported, as they do not contribute new medical or scientific information. Almost all of the reported cases have involved short Q-switched laser pulses of duration in the nanosecond range, and have produced intraocular hemorrhages, indicating that they were caused by energy levels exceeding threshold values. The clinical course of such injuries is described in the following sections. The clinical course of continuous-wave and subthreshold exposure accidents are less well defined.

A. OCCUPATIONAL LASERS

Lasers are widely used in laboratories and industrial processes, and these have been responsible for most of the reported laser eye accidents.[21,29,30,39,44,52,53,59,69,72,74,84,94,111,116,118,120,150,180] Several common elements characterize these injuries. Almost all involve at least some carelessness and could have been avoided by following standard laser safety practices. In most cases the victim was not wearing eye protection for various reasons, mainly comfort. Most injuries occur during alignment of the laser beam or other adjustment procedures. The victim is usually looking directly at the laser source, which is presumably why most reported injuries have been parafoveal. Occasionally, the beam takes an unexpected path, for example, when it is unintentionally reflected by a mirror or nearby object, such as photographic paper or plastic membrane. In some of the reported accidents, the laser device discharged unexpectedly. As these accidents happen in indoor settings, the eye is usually accommodated to focus on objects 50 to 200 cm away, with consequent enlargement of the retinal lesion size and a decrease in energy density. Because the distance from the laser source is short, the beam does not diverge significantly and the injury is usually unilateral.

Virtually all reported injuries have involved the retina and were caused by relatively low-power, pulsed Nd:YAG lasers operating in the visible and near-IR spectrum and emitting few to tens of millijoules per pulse. The following clinical and prognostic descriptions address injuries by this kind of laser. In contrast, there are remarkably few, if any, reported injuries from high-power IR lasers such as CO_2. This may be because the latter devices are heavier and nonportable, and are thus fixed in place with the beam normally not directed outward. Sliney has suggested that users have "greater respect" for these high-power lasers and, therefore, consistently wear eye protectors.[164]

In a review of pertinent data from published case reports, the following information was obtained. Among 61 laboratory and industrial accidents, five (8%) were bilateral. In nearly all cases, retinal or vitreous bleeding occurred. Damage to the central part of the macula occurred in 62 (93%) of 67 eyes. Seventeen (46%) of 37 eyes had initial visual acuity of 20/200 or worse. In 12 (32%) of 37 eyes, initial visual acuity was 20/40 or better, but a paracentral scotoma was observed. Short-term follow-up indicated marked improvement in acuity in 20 (95%) of 21 eyes. In 12 (55%) of 22 eyes followed up for more than a few months, visual acuity reached 20/25 or better, whereas only two (9%) of 22 eyes were blind.

Despite the large number of factors that determine the nature of laser injuries, the clinical courses described in the above reports are similar. While handling a laser device, the victim experiences a sudden and severe disturbance of vision in one eye, often preceded by a visible flash of bright colored light. In some cases there is an audible "pop." Pain is infrequently reported.[39,59,193] The accompanying psychological reaction of horror and shock is vividly described in an account by Decker.[59] Examination of the victim reveals markedly decreased visual acuity, commonly 20/200 or worse, and visual field defect. The anterior segment is typically unaffected[21,39,69,72,84,117]; only one report describes a small corneal subepithelial opacity, which accompanied a typical retinal lesion,[116] the significance of which is unclear. Intraocular pressure was measured in two cases and found to be normal.[21,116] Ophthalmoscopy shows single or multiple localized lesions of retinal edema, burns, or holes, typically in the macula, with subretinal, subhyaloid, or vitreous hemorrhage. The subsequent clinical course is characterized by marked improvement during a period of a few days to weeks, mainly because of clearing of hemorrhage and subsidence of inflammation at the site of injury. This is followed either by stable vision or by deterioration caused by late complications, as discussed below (Figs. 3 and 4). Infrequently, delayed-onset improvement of vision is reported.[139]

Interestingly, some authors have reported the incidental finding in laser workers of peripheral retinal lesions consistent with old laser injuries, although no recollection of such injuries could be evoked (Fig. 5).[39,44,74,193] Presumably, threshold laser injuries to the peripheral retina had been asymptomatic and had gone unrecognized. Accordingly, the number of accidents reported in the medical literature might not reflect their true incidence. It was previously thought prudent to have people who are at high risk of laser exposure undergo routine periodic ophthalmoscopic examinations to monitor for laser-induced eye injuries. In view of the symptomatic nature of visually significant laser injuries and the fact that treatment of laser-induced retinal injuries is unavailable, most authorities do not currently recommend periodic eye examinations for laser workers. Such examinations should, however, be performed before a potentially hazardous occupation is started and after its termination for medicolegal reasons.[11] The question of the optimal sequence of examinations for laser workers is as yet moot.

In two exceptional cases,[154] civilian pilots experienced temporary flashblindness after exposure to a 12- to 15-W argon laser that was being used in a light show on the ground. In one of these cases the aircraft was 3.5 miles from the laser source.

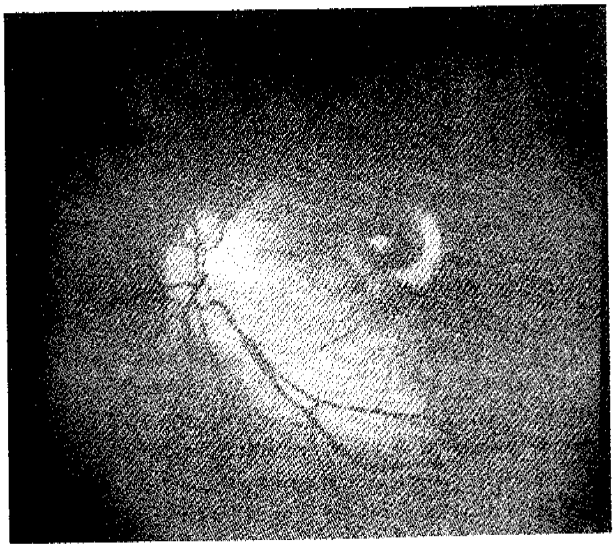

Fig. 3. An eye exposed to a Q-switched double Nd:YAG laser (532 nm at 14 mJ, 7 ns). Vision was lost immediately and never recovered beyond 6/120. Photograph was taken 2 months after injury, showing macular scar and the damage extending much further than the foveal lesion, presumably about 50 μm in diameter.

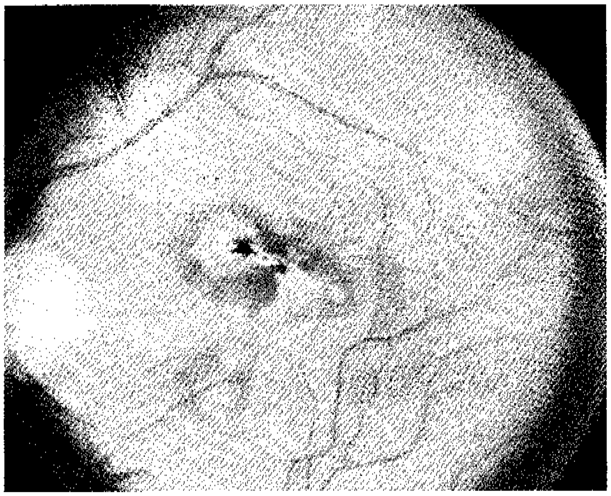

Fig. 4. An eye with four accidental 5-mJ exposures to Nd:YAG laser, 1 year after the injury. Scarring and contraction around the scars are evident (courtesy of the Medical Research Detachment, Walter Reed Army Institute of Research, San Antonio, Texas).

In recent years, low-cost hand-held laser pointers have become very popular, and their potential for eye damage has concerned ophthalmologists.[4,22,92,121,129,165] Laser pointers emit a continuous narrow beam of visible light, most commonly red light (670 nm for diode laser and 632.8 nm for helium-neon). The output power is commonly 1 to 5 mW; if shone directly at one's eye, retinal irradiance occurs, similar to that caused by staring directly at the sun.[165]

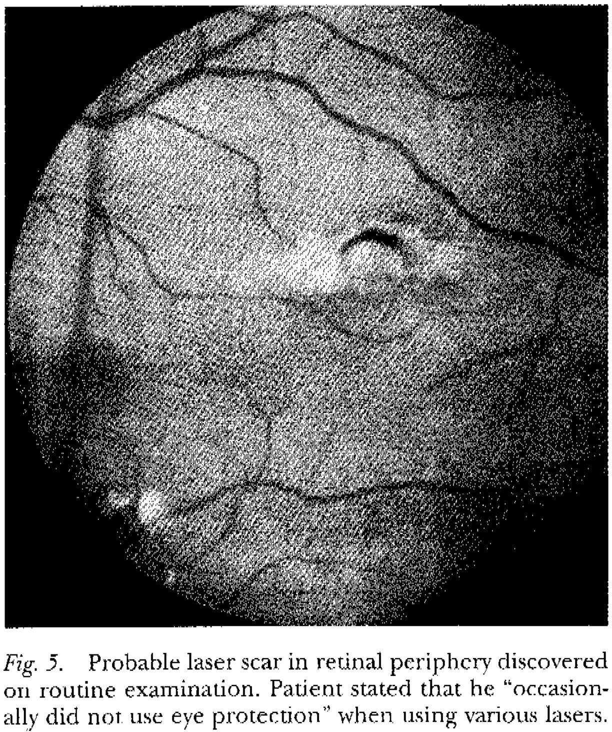

Fig. 5. Probable laser scar in retinal periphery discovered on routine examination. Patient stated that he "occasionally did not use eye protection" when using various lasers. There were no symptoms during the probable exposure or later. The case illustrates the importance of ophthalmoscopic examination before starting to work at occupations that entail laser exposure hazards.

Reports in the popular press of alleged eye injury by laser pointers have portrayed public fear and ignorance and media hype rather than facts.[129,137] The likelihood that an accidental exposure of the eye to such a device will result in permanent retinal injury is exceedingly small.[65,129] Lasers with this output power are incapable of causing retinal damage under normal circumstances, in which exposure is limited by the blink reflex and aversion response. Damage could theoretically occur on prolonged staring into the beam, whether unintentionally by color-blind individuals or intentionally. Mild thermal retinal injury might occur from a 5-mW laser if an individual purposely stared into the bright light for more than 10 to 20 seconds.[65,110,127] Recently, two cases have been published in which retinal damage was attributed to intentional prolonged staring into a laser pointer's beam.[121,194] At less than 1 mW, even longer exposures are not expected to cause irreversible damage. As the eye is most sensitive to wavelengths near 550 nm, laser pointers that use these wavelengths can achieve the same perceived brightness of current red-light pointers with a power of less than 1 mW. As these gradually become the market standard, the issue of retinal damage by laser pointers should disappear.[65,129]

More significantly, transient visual incapacitation can be caused by laser pointers through glare, flashblindness, and afterimages, especially when the exposed person is dark-adapted. This could lead to secondary damage; for example, an exposed driver might cause a traffic accident. Up to now there have been no reported incidents of such indirect damage. Laser pointers are, however, increasingly misused, for example, to distract drivers and basketball players, and have been reported to be commonly used against American pilots in Bosnia.[1]

The ophthalmologist caring for a patient with complaints attributed to a laser pointer exposure should bear in mind that visible radiation is not absorbed by tissues at the front of the eye, and, thus, symptoms of pain or irritation are likely caused by eye rubbing.

B. OPHTHALMIC LASERS

Ophthalmic laser systems have revolutionized the treatment of eye diseases. Laser photocoagulation is commonly used for treating diabetic retinopathy, age-related macular degeneration, retinal tears, and glaucoma. The process of photodisruption is employed in noninvasive iridectomy, posterior capsulotomy, and interruption of vitreous bands. Corneal photoablation is extensively used in refractive surgery. Diverse applications have been reported, including phacovaporization,[76] vitreoretinal surgery,[55] suture lysis,[122,138] dacryocystorhinostomy,[119] and measurement of flare and cells in the anterior chamber.[63] A promising new modality is photodynamic therapy, in which tissue is "photosensitized" by the intravenous injection of a dye and then irradiated at a wavelength that is maximally absorbed by the dye. Laser beams can then be used, at energies lower than those used for photocoagulation, to selectively induce occlusion of blood vessels in aberrant neovascular tissue[158] or tumors.[58]

Like many special procedures in the practice of medicine, however, these procedures are not without the potential for various types of complications.[148] Some complications are difficult to avoid, as they stem from the very effect used for therapy. For example, local spread of heat during retinal photocoagulation may cause rupture of Bruch's membrane with choroidal hemorrhage, or damage to the nerve fiber layer. Neurosensory deficit often results from delayed expansion of the original lesion.[43,57] These effects presumably account for the observed visual deterioration after treatment of juxtafoveal[16] or subfoveal[14,15] lesions. Energy spread during laser iridotomy or posterior capsulotomy can affect the nearby cornea, crystalline or artificial lens, or anterior vitreous face.[143]

An intriguing adverse effect has been reported regarding the effect of argon laser photocoagulation on the eyes of the ophthalmologist operating the laser. Acute reduction in color contrast sensitivity was observed after treatment sessions, which recovered in most cases, although a permanent threshold elevation was suggested.[36,88] One follow-up study did not corroborate this.[71]

Because of the controlled nature of medical laser procedures, true accidents involving unexpected injury to tissues remote from the focus of treatment have been rare. It is possible that such incidents have been underreported. Rubinfeld et al described a case of severe thermal burn of the cornea during retinal photocoagulation with use of indirect ophthalmoscopy, which led to perforating keratoplasty.[156] Less severe burns of the cornea and iris associated with this procedure were reported in five patients.[97] A case of corneal perforation during slit-lamp retinal photocoagulation was reported by Keithahn et al.[105] Widder et al described a case in which bilateral corneal injury occurred after skin resurfacing of the face by CO_2 laser.[190] Prendiville and McDonnell described a similar case of three healed corneal burns (one perforating) after CO_2 laser cosmetic blepharoplasty.[148]

Lens opacities have been reported after argon and krypton laser photocoagulation in adult eyes that had preexisting cataract.[114,133,163] The opacities were noted during or immediately after treatment and were stable, suggesting direct laser damage to lens material. Photocoagulation for retinopathy of prematurity has been reported to cause transient focal lens opacities and complete opacification of the lens nucleus and cortex.[51,60;147] These cataracts developed weeks to months after treatment in previously clear lenses and in some cases were progressive. The cause is unknown.

Cai reported two cases of accidental macular burn during laser treatment of the iris[44]; Liu et al described a similar case.[120] Whitacre and Mainster reported three cases of laser injury to unintended retinal sites during photocoagulation in eyes containing gas, caused by reflection of the beam at the gas-fluid interface.[189] Jampol et al reported the use of Q-switched Nd:YAG laser for interruption of a taut hyaloid membrane causing traction retinal detachment.[101] Such treatment, applied 2 to 3 mm from the retina, resulted in microperforation of a superficial retinal vein and a focal area of damage to the RPE.

C. MILITARY LASERS

The situation regarding laser injuries in military situations is graver than in civilian life. Lasers are very commonly used in the military, are used outdoors at very long ranges, and are often handled by people not well trained in laser safety practices. Furthermore, most laser-associated military activities involve the beaming of targets that usually contain people, some of whom are using binoculars and other magnifying optics, making their eyes vulnerable over many kilometers.

Several cases of military laser eye accidents have been reported.[21,44,73,87,104,117,123,139,168,173,174] All have involved lasers similar to those used in civilian laboratories, with pulses lasting nanoseconds, energies of a few tens of millijoules, and wavelengths in the visible or near-IR spectrum. Accordingly, the clinical course has been similar. Some differences, however, merit consideration.

Many of the accidents have occurred under circumstances that are unique to the military, in addition to negligence or careless operation.[87,104] Accidental exposure has occurred in the course of military exercises.[123,174] Lang et al reported a case in which a civilian was sitting in his car, looking through the windshield at a tank 25 m away.[117] He suddenly saw a bright red flash coming from the tank and immediately became aware of a decrease in vision in both eyes, more in the left. The source was a ruby laser range finder mounted on the tank, which presumably had emitted a single 20-mJ pulse of 20-ns duration at 694 nm. The calculated intraocular exposure was 10,000 times greater than the maximum permissible exposure listed in the ANSI standard.[11] It is interesting that, although both maculae were hit, one eye recovered its visual acuity almost completely, whereas the other remained legally blind.

Mader et al[123] and Stuck et al[174] described what is possibly the first and only case of eye injury caused by an enemy laser during actual combat. During Operation Desert Storm, a USA soldier was using a monocular laser range finder with his left eye to determine the distance to an Iraqi bunker, when he noticed a red flash from the bunker area and immediate loss of vision in his left eye (visual acuity, 10/400). He was later found to have findings consistent with a laser burn, a yellow-white spot and subretinal hemorrhage in the center of the macula. A contributing factor in this case was the magnification provided by the eyepiece of the range finder.

Military laser injuries are more likely to be bilateral.[73,87,117,123,200] This is in part because of the outdoor nature of the accidents, involving a beam that has diverged significantly from the source. In addition, some military laser devices produce a beam that is already a few centimeters wide at its origin. If the unlucky victim happens to stare directly at the source, both foveae will be damaged, with severe visual consequences. However, to date there is no report of bilateral blindness caused by a laser injury.

Because of the high pulse repetition rate of military lasers, the retinal lesions are likely to be multifocal. In this regard, an initial lesion at the periphery might lead to macular injury because of the instinctive tendency of the victim to turn his or her head toward the light source.[39,104,129] In contrast to the situation in laboratory accidents, the military victim's eye is unlikely to be accommodated; hence, the laser beam is sharply focused on the retina.

In two reported cases, laser retinal injury was the presumed diagnosis based on history and examination, although visual disturbance was not preceded by a visible flash and a laser source was not initially suspected.[87,117]

D. PROGNOSIS

As described earlier, laser radiation may cause variable damage to the retinal area that it strikes directly. In addition, the lesion spreads, as in any neural injury, because of the release of various noxious agents by the directly injured neurons. In the retina, the principal agent is probably the excitotoxic amino acid glutamate, the retina's chief neurotransmitter.[113] Glutamate and other agents, such as inflammatory mediators, spread to neighboring cells, destroying them and, thus, setting up a cascade that runs its course until the lesion becomes much larger than the original one.[111] This secondary degeneration, as well as the spread of the shock wave and heat from the initial lesion, is responsible for the considerable increase in morphological and functional damage caused by the primary lesion. Indeed, laser lesions have been shown to spread for many hours or days after the primary injury.[43,57,155]

After the lesion reaches its widest extent, a few hours or days after the accident, it begins to subside. Some of the cells that were not destroyed directly by the beam or by secondary injurious mechanisms recover, and so too, to a greater or lesser extent, do the visual functions of the eye. Subsidence of the retinal lesion lasts from a few weeks to months and is accompanied by absorption of periretinal and intravitreal hemorrhage, with resultant marked improvement in visual acuity. In the literature reviewed, early marked improvement in acuity occurred in 20 (95%) of 21 eyes.

Generally, the further the initial lesion is from the fovea, the greater the improvement. In one case, even when the initial lesion involved the central fovea with a dense scotoma, vision improved to 20/25 in 5 months.[69]

However, the development of late complications may be responsible for delayed worsening of visual function after the initial improvement. The development of chorioretinal scarring is the most frequently experienced severe complication.[21,44,74,104,116,120,175] Other complications include macular hole, which may remain stable or enlarge,[52,84,120,180] macular cyst,[128] macular pucker,[21,82,84,116,120,139] and preretinal membrane formation.[84,104,139] Interestingly, Thach et al described a full-thickness macular hole that closed spontaneously within 3 weeks after injury.[180] In another case, prominent macular pucker observed 3 months after injury had regressed considerably at 12 months, with marked improvement of visual acuity.[139]

Choroidal neovascularization is known to occur after retinal photocoagulation for various diseases[35,68,70,77] and has been produced experimentally in monkeys by continuous-wave argon laser.[157] Until recently, this complication had not been reported for laser accidents followed up for as long as 12 years.[21] Kuhn et al reported one case of accidental industrial YAG laser injury, in which a subfoveal choroidal neovascular membrane was revealed by fluorescein angiography 16 days after injury.[111] Complete resolution of the membrane was achieved after treatment with intravenous and oral corticosteroids.

Known complications of vitreous hemorrhage, such as hemosiderosis bulbi and glaucoma,[171] have not been reported after laser injury.

In the literature reviewed, 12 (55%) of 22 eyes followed up for more than a few months had a visual acuity of 20/25 or better, eight eyes (36%) between 20/30 and 20/100, and two eyes (9%) 20/400.

Stuck et al described a residual functional deficit after laser injury.[174] Contrast sensitivity and pursuit tracking performance were reduced in injured eyes, even after normal visual acuity had returned.

The psychological effects of laser exposures, even those not causing permanent damage to eyes and vision, have not yet been thoroughly investigated. These psychological effects are becoming more common with the widespread availability and use of laser pointers.

III. Military Lasers

A. THE LASER AS A WEAPON

The modern battlefield is permeated with laser radiation. Laser devices may cause eye damage in the course of accidental exposure, or they may be deliberately directed against personnel. Used as weapons, visually incapacitating lasers offer many advantages over conventional weapons.[26,179] The fired energy travels at the speed of light; if a laser pulse is fired at an aircraft traveling at the speed of sound from a distance of 1 km, the aircraft will move little more than 1 mm before being hit. When traveling through a nonvacuum medium such as air, the laser beam does spread, albeit very slowly, and can be tuned in such a manner as to create, at tactical ranges such as 1 km, an effective "photon bullet" 1 m across. In addition, the laser energy is delivered in a straight line of sight, not necessitating complex and costly control systems to calculate ballistic trajectory. These factors make the laser weapon both accurate and simple to operate. It can be used with relative ease to temporarily or permanently blind pilots inside an airplane or soldiers operating on the battlefield.

Laser weapons are silent and, if operated in the IR or UV spectrum, invisible. Their ammunition logistics are also very simple and convenient—a single battery pack carried by a soldier allows hundreds of shots.

Visually incapacitating laser weapons have some inherent disadvantages as well. They can be used only when the adversary is facing the user. The laser beam undergoes considerable scattering and is therefore substantially attenuated by water droplets, smoke, or dust.

B. CURRENT MILITARY LASERS

1. Auxiliary Laser Devices

Laser devices have been used by modern armies for more than two decades[87] to accomplish two main tasks: determining distance (range finding) and marking a target for delivery of laser-guided weapons (designation). Range finders emit a short pulse of energy, measure the time to detection of the pulse reflected from the target, and calculate the distance accordingly. Thousands of these devices are currently in use,[136] whether hand-held or mounted on tanks or aircraft. Laser target designators operate on a similar principle and are also widely used; the operator aims a laser at a target and the reflected energy is detected by a "smart" bomb, utilizing an electro-optical sensor that guides itself to the target. Although these systems are not designed primarily for antipersonnel use, they can potentially cause eye injury, whether by accident or purposely under battlefield conditions. The laser most frequently used is the pulsed Nd:YAG, which produces wavelengths in the near-IR range (1,064 nm) and, thus, is intrinsically not safe for eyes. There are many published reports of damage caused by the Nd:YAG and other lasers.[24,87,104,117,123,139,154,168,175] This wavelength is best suited for the specific tasks of these devices, since far-IR radiation is absorbed by water and is, thus, attenuated by atmospheric mist, fog, and rain. However, in order to improve eye safety, devices that use longer wavelengths are now used and developed.[102]

The output power of these military devices has occasionally been published. One report describes a target designator delivering 50 mJ in a 20-ns pulse.[104] Anderberg et al used a "standard military ruby range finder," which emitted pulses of 180 mJ in 25 ns.[25] They showed that it was capable of causing vitreous hemorrhage in pig eyes from a distance of 850 m when a pair of binoculars was placed in front of the eyes. The safe unaided viewing distance for a USA army's hand-held range finder with an output of 15 mJ was reported to be 1,100 m[102]; with use of ×7 binoculars, the distance is 8,000 m.

2. Laser Weapons

Laser weapons are being developed to damage battlefield electro-optical sensors and visually incapacitate soldiers. Military forces use many electro-optical surveillance instruments, such as night vision apparatus and television cameras. All of these devices employ light-sensitive sensors that can be damaged by laser radiation. Consequently, laser systems are developed for disabling these sensors. Most of these sensors operate at wavelengths of 400 to 1,400 nm, the same as the most common sensor on the battlefield—the human eye. Thus, antisensor weapons can cause eye damage.

Most of the existing data relate to American laser weapons, as the Americans have been more candid about their laser development program. It is known, however, that many other countries are developing, and some are fielding, similar devices with the same purposes. Some examples of reported systems are described below, based on reports in military and laser technology journals during the past decade. It should be emphasized that these weapons currently exist in limited quantities or for prototype use[6,7,91,106,136,140,162,170,179] and have not been put into the field in significant numbers.

Stingray was reported to be an American vehicle-mounted system weighing 160 kg.[91,136,179] It could scan the scene with a wide, low-power laser beam. Once the beam enters the optical train of an enemy optical or electro-optical system, a small fraction of the light is reflected and detected by the weapon, which instantaneously locks on the target, sharply increases its output, and narrows the beam. The energy may overload or damage the electro-optical sensor and, thus, temporarily or permanently disable the targeted device. The laser similarly detects and hits binoculars, with potentially dire consequences to the eyes behind them.

Improvements in laser technology have led to smaller and more powerful devices. In 1990, it was reported that the USA army had tested two portable systems, named Cobra and Dazer, in the form of a gun connected to a battery backpack.[31,136,179] The Dazer uses an alexandrite laser and can be tuned to several different wavelengths, so that it is exceedingly difficult to protect against it. Reports in 1995 described the production for the USA army of a small device that can be mounted on a standard M16 rifle, named Laser Countermeasure System.[106]

The power output of these newer devices is shrouded in secrecy. Compared to range finders and designators, they employ the laser beam as the primary kill mechanism rather than as an aid to other weapon systems; thus, their output is expected to be significantly higher.

There are reports of other nations developing antisensory laser weapons.[6,7,141] The British navy allegedly caused the loss of some Argentinian aircraft during the Falklands war by dazzling the pilots,[78,144,184] and Soviet ships caused at least temporary visual deficit of American pilots flying in the Hawaii area.[17-19] American pilots flying over Bosnia have reported numerous incidents in which lasers were aimed at them from the ground.[1] During the Persian Gulf war, the allied forces used laser eye protection,[7] and at least one American soldier was probably injured by an Iraqi laser source.[123]

In March 1995, a Chinese manufacturer marketed a laser device at two open arms exhibitions,[5] specifying in its fact sheet[48] delivery of two wavelengths simultaneously at five pulses per second at greater than 15 mW, and an effective distance of 2 to 3 km for direct human eye injury and of 10 km for flashblinding. This marked the first instance of overt marketing of such a system and open admission in the sales literature that "one of its major applications" is to "injure or dizzy" targeted individuals.

Conceptually, laser weapons that can only dazzle, without causing permanent blindness, may be developed for civilian tasks such as riot control.[2,107] This may not be realistic, however, since a device that can dazzle from afar is theoretically able to cause significant damage if used from a shorter distance.[3]

At present, there is no deployed laser with enough output energy to cause significant damage to the skin or the external eye from tactical distances. However, in the near future, weapons capable of burning or vaporizing a person from a distance may appear in the military field. Research on such high-energy lasers is being conducted as part of the American Strategic Defense Initiative[136,170] to be used against short-range and long-range ballistic missiles.

IV. Protection

Safety standards have been developed for ocular exposure to UV, visible, and IR radiation.[11,166] The internationally accepted laser safety documents are the latest version of the American National Standards Institute standard for the safe use of lasers (ANSI Z. 136.1)[11] and its European and international equivalents.[12,13] Complete protection against accidental laser injury is possible, provided that the characteristics of the instrument and its mode of employment are known. In nonmilitary circumstances, this is relatively simple, and the almost universal adoption of the protective standards has resulted in the relative rarity of laser accidents. In the military sphere, effective protection is currently lacking. This is because of the nature of the specific environment, use in the open field, and the need, even without the intention of causing eye injuries, to point laser radiation in the direction of people.

Following is a short discussion of the practical options for eye protection.

A. FILTERS

Since laser radiation is produced in near-monochromatic bands, the obvious means of protection is the use of wavelength-specific filters.[23,91,136,179] These filters either absorb or reflect light energy at a specific wavelength, yet allow sufficient light of other wavelengths to be transmitted. They are widely used in goggles to protect operators of lasers in medicine, industry, and laboratories. The main limitation of these protective devices is the reluctance of the operating personnel to wear them. This has led to the production of increasingly lightweight and comfortable goggles.[34]

The significance of wavelength specificity is vividly illustrated by Wolfe[193] in the case of a physicist who was operating a neodymium laser with Raman cell. He was wearing goggles that protected him from neodymium (1,064 nm) and frequency-doubled neodymium (532 nm) when he was exposed to a laser beam that had been shifted by the Raman cell to 770 nm. He sustained injury to the parafoveal retina of one eye. Lam et al[116] described two cases of retinal injury by Nd:YAG laser in which the victims were wearing protective goggles for argon lasers.

On the battlefield, filter defense may not be satisfactory. First, the wavelength of the enemy laser device must be known for the correct filter to be used. This can be detected by special sensors, which are already in use,[23,30,34] but the information will be obtained only after the enemy laser has already been used. In addition, it is easy to overcome the protection offered by filters by using more than one laser wavelength in a system. A filter that effectively blocks more than three wavelengths in the visible spectrum severely diminishes the amount of light entering the eye and, thus, would force a soldier wearing this filter to abandon his or her assigned task. Moreover, filter protection may be rendered impossible by frequency-agile lasers, which can be tuned manually to operate at any wavelength in the visible spectrum. An effective filter against such a laser will have no visible transmission!

Protective eyewear has been supplied to combat units in some countries and is under continuing development.[7,23,96] Current models protect against several wavelengths most likely to be encountered on modern battlefields, such as those of range finders and target designators based on Nd:YAG and ruby lasers, while causing minimal visual impairment. Another available system is based on a detector that distinguishes between a few specified laser bands, which together cover the relevant spectrum, with corresponding goggle outserts.[34] Since these are passive countermeasures, they must be worn for long periods of time in anticipation of a laser attack. This is found to impair performance and decision making.[42,181]

The optimal laser filters will be transparent under normal circumstances and will be switched on and block light transmission when they encounter coherent radiation. Such filters have been in the process of development for many years. To date, there is no such filter available and none is likely in the foreseeable future. The main technical limitation is the necessity of being switched on within nanoseconds or less, with high unit cost being another restraint.

B. INDIRECT VIEWING

Soldiers can avoid laser exposure if they view the battlefield through closed-circuit television or some other sensor and not directly with their eyes. If laser weapons are used, only the light-sensitive part within the viewing device will be "blinded." The limitations of this form of protection are obvious. They are not suitable for infantrymen, they limit the visual field, and they are liable to be damaged by the same radiation they are protecting against.

C. EYE PATCH

Wearing a black patch over one eye to guarantee its safety in case of hostile laser use may seem odd. However, in a very difficult situation, such as essential infantry action in a place where the enemy is using laser in the antieye mode, and if no other means of protection exists, it may be the only available solution. This method has clear disadvantages, such as loss of depth perception and reduction of visual field.

D. NONSPECIFIC METHODS

Given the current state of protective devices, potentially exposed soldiers may have to change their visual behavior, for example, by minimizing or avoiding direct viewing of enemy positions. Since this is an impossible measure to maintain on the battlefield, active countermeasures must be used, such as the deployment of smoke, which absorbs and diffuses the laser beam. Interestingly, these effects are dependent on the smoke compound, its particle size, and the laser wavelength. Smokescreens, however, are weather-dependent and temporary, and they obscure sight. Suppressive fire can be used against laser weapons. Such weapons, however, are small, silent, highly maneuverable and, thus, difficult to detect and fire upon.

In summary, protection against laser weapons presents a difficult problem, which so far has remained largely unsolved, despite intensive research. Consequently, the use of lasers may have a decisive influence on the battlefield, as is the case with other unconventional weapons. The side that uses mass-deployed and frequency-agile laser weapons is likely to have the upper hand, and affected units may suffer panic and subsequent breakdown.

V. Management

A. MEDICAL MANAGEMENT

Current medical therapy for retinal injury is mainly limited to corticosteroids at an undetermined regimen. This treatment is given with the rationale of reducing the cellular inflammatory response to injury, thus possibly minimizing its extent. It has been associated with diverse results, including complete recovery of vision.[94,200] Other anecdotal case reports describe the use of antioxidant vitamins and vasodilator drugs.[29,44,116,120] However, corticosteroid administration has been the preferred treatment regimen reported in most cases, even though its effects have not been properly established in clinical studies. Corticosteroids have been used successfully in experimental animal models of various laser retinal injuries. Lam et al reported a beneficial effect of treatment with methylprednisolone given as an intravenous bolus of 30 mg/kg and a maintenance dose of 5.4 mg/kg per hour in laser injuries of nonhuman primate retina.[115] Morphologically, treated retina showed rapid reestablishment of retinal and choroidal vasculature, proliferation and organization of RPE and reformation of the outer limiting membrane, less macrophagic activity, and reduced photoreceptor damage at the periphery of the lesion.[115,177] Naveh and Weissman treated rabbits after a single retinal argon laser lesion with daily intramuscular dexamethasone, 0.5 mg/kg of body weight, and found reduced vitreal accumulation of protein and prostaglandin E_2 compared to controls.[142] Wilson et al found that intravitreal injection of triamcinolone reduced breakdown of the blood-retinal barrier after panretinal photocoagulation.[191] Continuous intravitreal infusion of corticosteroids was reported by Ishibashi et al to inhibit subretinal neovascularization after laser-induced retinal lesions in monkeys.[99]

Other studies have questioned the efficacy of corticosteroids in laser injury. Rosner et al reported that systemic corticosteroids had only a short-term effect on argon laser–induced lesions in the retinas of pigmented rats.[155] Corticosteroids were shown to promote sparing of neurons after mechanical injury but to interfere with regeneration of neural tissue, for which inflammation is necessary.[95] Marshall noted that corticosteroids slowed the regeneration of the outer blood-retinal barrier by RPE cells and suggested that corticosteroids not be used to treat retinal laser burns until more data become available.[130] Recently, Schuschereba et al reported that megadoses of intravenous corticosteroids have a deleterious effect on the prognosis of argon laser–induced retinal injuries in rabbits.[161]

Recent years have seen the introduction of new compounds, known as "neuroprotective" compounds,[49,50,56,64,134,159] that decrease the natural secondary spread of any injury in neuronal tissue, including the retina, as described previously in the section on prognosis. One such neuroprotective compound, the glutamate-receptor blocker MK-801, was found to limit the retinal lesion caused by laser exposure in an animal model of an argon laser–irradiated pigmented rat retina.[169] Testing of other potential neuroprotective compounds with the use of a similar model showed that methylprednisolone had only a temporary effect, and that the antioxidant enzyme superoxide dismutase and the calcium-channel blocker flunarizine were ineffective.[154] Because MK-801 is too toxic for human use, experiments are being conducted to evaluate other glutamate antagonists for their neuroprotective effects on the laser-irradiated retina. Deferoxamine has been found experimentally to favorably affect the course of experimental laser injuries.[161]

Growth factors and similar compounds have also been used experimentally to treat laser-induced retinal injuries. Schuschereba et al reported that intravitreal injection of human recombinant fibroblast growth factor after laser injury in rabbits accelerated healing of the blood-retinal barrier and reduced photoreceptor loss.[160] The above observations may pave the way for future therapy of laser injuries, whether accidental, malicious, or iatrogenic.

B. SURGICAL MANAGEMENT

Surgical intervention may be considered for removing vitreous and periretinal hemorrhages, but its exact role is difficult to establish. Typically, hemorrhages resolve spontaneously within a relatively short time, from 2 weeks[28,116,128,180] to a few months.[74,94,104,116,117] In one report,[180] the presence of subretinal and preretinal blood was considered helpful, as it may have contributed to the unusual spontaneous closure of a full-thickness foveal hole, 180 μm in diameter, by acting as a "tissue glue." Thus, it might be worthwhile to postpone surgery unless prompt restoration of vision is required. On the other hand, in some cases, resorption of blood is accompanied or followed by the formation of a chorioretinal scar, epiretinal membrane, or retinal hole. Gagliano et al found greater retinal damage in experimental laser lesions associated with subretinal hemorrhage than in nonhemorrhagic lesions of comparable energy, with the difference apparent as early as 1 hour after exposure.[75] They recommended that such lesions be surgically treated immediately. The presence of blood may contribute to these processes by virtue of disturbed retinal architecture, induction of fibrosis, and release of breakdown products such as iron.[171]

The use of the Nd:YAG laser has been suggested in cases of contained subhyaloidal[74] or sub–internal limiting membrane[103] hemorrhages, to allow the hemorrhage access to the vitreous body, where its resorption will be accelerated and the macular effect reduced. This procedure has been reported in a few cases,[73,103,110] but not in laser injury.

Isernhagen et al reported the results of vitrectomy for nonclearing vitreous hemorrhage not associated with retinal or choroidal vascular disease.[98] Vision improved in 98% of cases, but the treatment was associated with a number of complications.

The role of retinal surgery is similarly unclear. Custis[54] reported unsuccessful surgery for a laser-inflicted macular hole with localized retinal detachment. Ciulla and Topping reported a case of macular hole operated on approximately 3 weeks after laser injury, with resultant improvement of visual acuity and significant reduction in scotoma size.[52] Epiretinal membranes that develop after laser injury may regress spontaneously, with[139] or without[21] improvement in visual acuity.

VI. Ethics

The ethical implications of laser weapon use and development have been considered by the United

Nations, the International Red Cross, government and military officials, human rights groups, and ophthalmologists.[7,9,10,27,46,81,106,128,170,178] Although it is unlikely that laser weapons can blind in the ophthalmologic or lay sense of the word, some agencies have proposed a total ban on blinding laser weapons.[27,106] Some groups have campaigned for the cancellation of "ongoing research and development of tactical laser weapons because of their potential use as blinding antipersonnel weapons."[27] They maintain that laser weapons should be considered needlessly cruel weapons and that the time to ban them is now, before they are produced in large numbers and eventually fall into the hands of terrorists and street criminals.

Officials in the USA have denied that the Laser Countermeasure System or other laser systems are intended primarily for use against enemy troops.[6] Furthermore, they have expressed concern that a ban would effectively prevent commanders and soldiers from deploying any lasers on the battlefield, even for use as range finders; if an enemy soldier were to be inadvertently injured, they could face investigation and even war crime charges. Another argument against a total ban is that, in a battlefield permeated with electronic sensors and guided systems, laser countermeasures can save lives on the side using them. Moreover, contrary to more conventional munitions, the ability to focus the destructive power of the laser beam enables it to reduce collateral damage to civilians and property. Military officials have been quoted as saying that it is better to blind than to kill.[6]

In September 1995, a United Nations–sponsored international conference was held to review the Conventional Weapons Convention and offered an opportunity to deal with the potential threat of laser weapons before it fully evolved. At the conclusion, the consensus protocol read: "It is prohibited to employ laser weapons specifically designed, as their sole combat function or as one of their combat functions, to cause permanent blindness to unenhanced vision . . . The High Contracting Parties shall not transfer such weapons to any State or non-State entity . . . [and] shall take all feasible precautions to avoid the incidence of permanent blindness to unenhanced vision . . . Blindness as an incidental or collateral effect of the legitimate military employment of laser systems, including laser systems used against optical equipment, is not covered by the prohibitions of this protocol."[8] These results were considered a "step in the right direction,"[27] but the exemptions and loopholes in the agreement allow the continuing development and battlefield deployment of laser devices and weapons.

It should be noted that the hazard of ocular injury from the accidental or deliberate use of laser devices can be significantly reduced if these devices are made to employ only eye-safe wavelengths, i.e., longer than 1,400 nm. In principle, all laser-guided and laser-based weapons could be made eye-safe. Under such conditions, no army could explain enemy eye injury as a by-product of laser use for a different purpose. Such a solution is probably impractical, however, because of the enormous cost associated with converting all existing military laser devices. Moreover, some devices, such as cameras and television viewing systems, will always use visible light sensors, and their justifiable laser counterweapons would be capable of inflicting eye damage.

VII. Conclusion

Laser devices are a common and essential part of modern medicine, industry, military, and everyday life. This leads to an increasing number of laser-related injuries. Laser radiation is mainly hazardous to the eye, because the energy focuses on the retina. Consequently, the vast majority of injuries have been ophthalmic. So far, laser eye injuries have been relatively few because of strict safety regulations.

In the future, however, many more injuries are expected, especially if laser weapons are employed. Ongoing research is expected to better define the mechanisms of tissue damage by laser and improve existing therapy and protection.

Method of Literature Search

For the literature citations in this review, we relied mainly on articles in personal collections (M. Belkin). In addition, we searched MEDLINE, using multiple search words, including *laser*, *retina*, *cornea*, *damage*, *injury*, *accidental*, and *complication*. Relevant conference proceedings and government reports were hand-searched. We reviewed all articles published in the English language. Abstracts of selected articles in languages other than English were used and are noted as such in the reference list.

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