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Optical radiation, with particular reference to lasers

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INTRODUCTION

The wavelengths covered by optical radiation range from 1 nm to 1 mm. This wavelength region includes not only the visible part of the electromagnetic spectrum, but also the ultraviolet (UV) down to the soft ionizing X-ray domain, and the infrared (IR) up to the radiofrequency domain. The region from 1 nm to 190 nm (vacuum UV) will not be discussed because it is completely absorbed in air and consequently has no direct biological effect.

There are quite a few reasons for treating this wavelength region as a separate entity, though any exact boundary is to a certain degree arbitrary. Optical radiation is produced by several radiation sources, such as conventional incandescent, fluorescent and phosphorescent lamps, electric arcs, and lasers. It is this last source that has engendered the greatest concern from the point of view of radiation protection.

As indicated, the boundaries of the optical radiation region cannot be precisely defined. Spectral designation schemes differ; the broad spectral regions defined by physicists such as "near" or "far" IR *(1)* are useful in discussing sources, whereas the CIE bands such as UV-A or IR-B relate to biological effects only *(2)*. Both schemes are used in this chapter.

In contrast to X-rays, optical radiation is essentially nonionizing. Its action is either photochemical (as in the UV) or thermal (as in the IR); the visible region is a transition region characterized by both effects.

In contrast to radiofrequency radiation, optical radiation usually acts at the surface. Penetration of the skin is mostly restricted to a few millimetres or less. The eye is an exception in that it admits visible energy into the body. Even in this case the penetration rarely goes beyond the retinal pigment epithelium.

Until this century, the principal source of optical radiation was the sun, but solar radiation was not considered very dangerous, primarily because of protective avoidance reactions naturally built into the organism and the development of adaptive pigmentation. The development of artificial radiation sources, however, has made the protection problem more urgent. In the early 1920s the first health protection standards were laid down to protect against overexposure to the UV radiation and visible light produced by welding arcs, and against the near-IR radiation related to the so-called "glassblowers' cataract". When Meyer-Schwickerath in 1954 *(3)* produced retinal lesions with a carbon arc light source, it became impossible to avoid the conclusion that even commonly used equipment can be hazardous. Although hazards and protective procedures relating to lasers will be emphasized in subsequent parts of this chapter, most of the material is also applicable to non-laser optical sources.

The acronym "laser" (Light Amplification by Stimulated Emission of Radiation) is commonly applied to devices that emit an intense, coherent, directional beam of "light" as a result of a process whereby an electron or molecule undergoes a stimulated quantum jump from a higher to a lower energy state, causing a spatially and temporally coherent beam of optical radiation to be emitted. Some types of laser can deliver optical radiation in such short-duration pulses and/or be so restricted to non-visible radiation that the sensory systems are completely bypassed as a protective means. Although the biological effects to be described can be produced in principle by all types of optical radiation source, it should be particularly emphasized that laser sources often present new and more potent health hazards.

In general, a laser consists of an active medium in a resonant optical cavity and a source of excitation energy. To achieve laser action, the active medium is excited. A pattern of electromagnetic waves builds up to a very high intensity in the resonant cavity by reflections from the mirrored end-windows, one of which is deliberately made less reflective than the other. Most electromagnetic waves built up between these two windows radiate out through the less reflective window. The cavity length does not completely determine the output wavelength, which is small compared with the cavity dimensions, but for every system there is an opimum cavity dimension. The output wavelength will always be within the fluorescent line-width of the active material, but the cavity dimensions can favour a particular wavelength.

Various solids, liquids, gases and diode junctions have been found which, by proper choice, allow one to achieve stimulated emission at distinct wavelengths throughout the visible, UV and IR spectrum. Depending on the active medium and system design, the emission duration can vary from single pulses as short as 10^{-14} seconds to continuous wave. As a simplification, in addition to the continuous-wave mode, where the time of exposure may vary from a few milliseconds to seconds, minutes or longer depending on conditions, there are four types of pulsed laser depending on the mode of operation: ultrashort pulses (exposure duration 0.01–15 ps); mode-locked (an envelope of ultrashort pulses in which the envelope duration ranges from 10 to 100 ns); Q-switched (exposure duration between 1 and 100 ns); and normal multiple-spike mode (in which the envelope of random pulses ranges from 100 μs to 30 ms) *(4)*.

Information on the potentially hazardous effects of optical radiation, and guidelines for practical protective measures against such hazards, are included. In these guidelines the acceptable exposure levels for irradiation are based on a consensus of opinion among experts after evaluation of the currently available biological threshold data. These form the basis for current decisions, permit investigators to judge where additional information is needed, and give responsible experts a starting point for assessing the value of new data. In practice, the use of optical radiation seldom permits personnel to measure readily the parameters relevant to exposure levels; hence more practical means of protection will be proposed, based on the establishment of classes of optical radiation sources defined in terms of the degree of hazard involved.

Secondary effects, which under some circumstances may be much more hazardous than the actual laser radiation, are not dealt with. These fall outside the scope of the present publication because many, if not all, are well recognized and are already the subject of properly codified safety procedures. These secondary effects include electric shock from insufficiently insulated high-voltage parts of lasers, injuries from the cryogenics, implosion or explosion accidents with arc lamps, respiratory hazards from vaporized materials, or falls at construction sites resulting from the dazzling effect of laser beams. All these examples and many more have been reported and are far from imaginary. Protection measures should be taken, of course, but relative to a particular apparatus and its specific method of operation.

LASERS IN MEDICINE

Lasers have been used in ophthalmology for a long time. For photocoagulation, argon and krypton lasers have replaced the ruby laser and the xenon-arc coagulators. With the growing practice of inserting intra-ocular lenses in patients after extra-capsular cataract surgery, the removal of secondary cataract (i.e. cells on the lens capsule that create opacities in the visual axis) with neodymium–YAG lasers has become common. By creating a plasma disruption of membranes, neodymium–YAG lasers have also been used for cutting vitrous strands and preretinal membranes.

The use of the excimer laser for corneal refractive surgery is now being developed.

In general surgery, as well as in urology, the use of CO_2 lasers to replace the scalpel in heavily vascularized tissues is now common. Development in these areas is rapid and other lasers, with or without the use of vital staining to enhance the effect, will soon be in use.

These lasers are also being used in plastic surgery, and a number of different lasers are already used in endoscopic treatment of various disorders. There are stringent regulations in force to protect the eyes of both patients and personnel.

LASER APPLICATIONS

The extremely collimated character and generally high degree of monochromaticity of the laser beam make this device of potential value in industrial, military and communications applications. It is beyond the scope of this chapter to include detailed discussions of all laser applications. Reference to the books by Charschan *(5)* or Goldman *(6)* would be useful. It can be generally stated that lasers are used in communications, precision measurement, symbol recognition, radar systems (lidar), guidance systems, range finding, firing simulation, metal working, photography, holography and medicine. The medical uses include treatment of the eye and skin, various diagnostic techniques, and surgery of the skin and internal organs; in dentistry, enamel scaling, bridge work, etc.; in industry, welding, drilling and cutting various materials; in communications, long-distance transmission; and in geodesy, accurate surveying. Some information on laser applications is given in Table 1.

Lasers do not at present constitute an environmental hazard to the uninformed public to the same degree as air pollution, noise or radioactive fallout, except under rather special circumstances such as laser illumination at entertainment spectacles and holographic public displays, range-finding at military installations or commercial airports, satellite tracking, air turbulence and pollution studies, and processing of materials such as metals and plastics. As the use of lasers increases, however, so will the possibility that a larger proportion of the population will be exposed.

Table 1. Typical laser applications

Area of use	Personnel involved
Business offices	Office workers
Communications	Communication engineers
Construction	Surveyors, equipment operators, sewer pipe installers, ceiling installers
Dentistry	Researchers, technicians
Geodesy	Aircraft pilots, surveyors
Holography	Researchers, photographers, artists
Materials processing	Processing engineers and machine technicians
Medicine	Physicians, surgeons, paramedical personnel, patients
Military	Researchers, troops during manoeuvres, aircraft pilots
Retail establishments	Sales clerks
Service and maintenance	Repair technicians

BIOLOGICAL EFFECTS

Mechanisms

Several mechanisms are involved in producing a laser lesion. The initial physical effects of laser irradiation are known to include thermal, thermo-acoustic, optical breakdown or photochemical effects. The initial physical trauma is followed by the biological reaction of the tissue itself. The types of physical trauma may differ, but only a few types of biological reaction occur, that is, different types of physical insult may call forth identical physiological reactions from the tissue. This tends to mask the differences in physical causation *(7)*.

There may also be amplifying factors in the biological reactions to the physical trauma. These include reactions to thermally denatured protein or other parts of injured cells, and increased cellular activity resulting from increased tissue temperatures accompanied by diminished cell survival. In the case of the photoreceptors themselves, the stimulation by light itself may cause a similar increase in metabolic rate. This deleterious effect of light may be synergistic with a similar effect caused by a rise in temperature. Many models exist that include both physical and biological processes and each is supported by some data, but no such model explains all types of damage. Indeed, there is good reason to suppose that several types of damage mechanism operate simultaneously or sequentially, so that no single theory can be expected to predict all possible situations where laser damage will occur. Thus, accumulation of large amounts of experimental data has become a prime necessity for the largely empirical formulation of exposure limits.

One important consequence of interaction of a laser beam with tissue is denaturation of protein, the extent of which is related to the incident energy per unit area or power per unit area and duration of exposure. The potential for injury to tissues also depends on the "accessibility" of the tissue to the radiation, which is a function of the depth of penetration of the radiant energy. When laser radiation impinges on tissue, the absorbed energy produces heat, and the resultant rise in temperature can easily denature tissue protein. The absorption of IR, UV or visible energy in tissue is not homogeneous, and the thermal stress is greatest around those portions of tissue that are the most efficient absorbers. Rapid and localized absorption may produce enough heat to boil the tissue water. The resultant steam production can disrupt cells or even produce dangerous pressure changes in an enclosed and completely filled space such as the eye or skull.

Another interaction mechanism is an elastic or thermo-acoustic transient pressure wave. As the laser pulse impinges on tissue the energy, through thermal expansion, produces waves (acoustic transients) that can rip and tear tissue and, if near the surface, can send out a plume of debris from the impact.

Non-linear optical breakdown with the creation of a plasma can occur even in the transparent media of the eye when local irradiances exceed 10^{16} W/m^2. This process has been employed surgically to cut membranes inside the eye.

Photochemical reactions result in activation of molecules by the capture of quanta of energy. Such capture constitutes the primary event in a photochemical reaction. Some of the photochemical reactions induced by laser exposure may be abnormal, or exaggerations of normal processes.

All of these mechanisms have been shown to operate in the retina, and indeed the safe exposure levels reflect their different effects.

General pathophysiology

An extensive bibiliography on the biological effects and hazards associated with lasers is available, including books by Gamaleja *(8)*, Goldman *(6)*, Sliney & Wolbarsht *(9)*, and Wolbarsht *(10–12)*. Sliney et al. *(13)* have prepared a bibliography consisting of 2795 references in the published literature organized into subject categories related to general biological effects, effects on the eye and the skin, laser safety, laser propagation in the atmosphere, and laser measurement.

So far, experimental work on animals has not indicated genetic changes, although malignant transformation has been suggested *(14–16)*. Such effects have not as yet been seen in man.

It is generally considered that the biological effects resulting from exposure to lasers are primarily a manifestation of a thermal response or photochemical reaction. Of special interest is the information on acute exposures to the eye and skin which, for the most part, has been obtained from research on experimental animals. There is little documented evidence from accidental exposure of man, but the increasing numbers of incidents occurring during therapeutic use should provide additional information.

The pathophysiological effects of optical radiation may be divided into a small number of categories, depending on the section of the spectrum within the optical radiation domain and on the part of the body affected. Table 2 provides a brief summary of the effects on the eye and on skin.

Table 2. Pathophysiological effects of optical radiation

Photobiological spectral domain	Effects on: eye	Effects on: skin
UV-C (100–280 nm)	Photokeratitis	Erythema (sunburn), skin cancer
UV-B (280–315 nm)	Photokeratitis, photochemical cataract	Increased pigmentation, sunburn, skin cancer, accelerated skin aging
UV-A (315–400 nm)	Photokeratitis, photochemical cataract	Pigment darkening, sunburn, photosensitive reactions, skin cancer, accelerated skin aging
Visible (400–780 nm)	Photochemical and thermal retinal injury	Pigment darkening, photosensitive reactions, skin burn
IR-A (780–1400 nm)	Cataract, retinal burn	Skin burn
IR-B (1400–3000 nm)	Corneal burn, aqueous flare, cataract	Skin burn
IR-C (3000–10^6 nm)	Corneal burn	Skin burn

Adverse effects on the eye

Potentially the most serious hazard from optical radiation is exposure of the eye. This is particularly important in the visible and near-IR regions of the spectrum, but there are also serious problems in the other regions.

Excessive UV exposure produces photophthalmia (photophobia) accompanied by redness, tearing, conjunctival discharge, corneal surface exfoliation and stromal haze. This is the syndrome of photokeratitis, often called "snow blindness" or "welders' flash". In the UV-B and UV-C regions this photokeratitis is the primary result of excessive acute exposure *(17)*. The action of the UV-B and UV-C radiation is usually photochemical rather than thermal, since the resulting temperature rise from exposure appears to be negligible. UV-A can produce erythema *(18)* by both photochemical and thermal mechanisms.

In the visible region the cornea, lens and associated eye media are largely transparent as they neither absorb nor scatter light to any great degree *(19)*. Only a small part, perhaps 5%, of the radiation that passes through the eye media is used for vision; the greater part is absorbed in the pigment granules in the pigment epithelium and the choroid, which underlies the photoreceptors (the rods and cones). The absorbed energy is converted into heat. If this absorbed energy becomes too great, tissue damage (usually referred to as retinal burn) can develop. Until relatively recently, only the sun was bright enough to cause retinal injury, and then only as a result of prolonged viewing. However, the availability of compact arc sources and lasers has greatly increased the danger of retinal burns. There is little doubt that the temperature rise in the chorioretinal tissue is the major factor in causing threshold damage, at least for short exposures.

A retinal injury occurring in the macula must be considered a serious trauma, since the visual functions are most highly developed there. On the other hand, similar damage at the periphery will often have little if any functional significance; even a large blind spot at the periphery has only a trivial effect on vision unless a haemorrhage appears. The damage caused by optical radiation may be one of many degrees of severity, and the extent of subsequent recovery may vary from none to complete restoration of normal function.

A transitional zone between retinal effects and effects on the anterior portion of the eye begins at the far end of the visible region and extends into the IR-A region. In the IR-B region both lenticular and corneal damage is seen. The ocular media become opaque to radiation in the IR-C region as the absorption by water, a major constituent of all cells, is very high in this region. Thus, in this region the damage is primarily to the cornea. For the longer wavelengths the IR damage mechanism appears to be thermal. The CO_2 laser at 10.6 μm in its action on all materials containing water exemplifies the thermal nature of the damage. In the IR-C region, as in the UV-A and UV-B regions, the threshold for damage to the skin is comparable to that of the cornea. The damage to the cornea, however, is much more disabling and of greater concern *(7)*.

Adverse effects on the skin

The large skin surface makes this structure readily accessible to both acute and chronic exposures to all forms of optical radiation, which can produce skin damage of varying degrees. The use of numerous different types of laser for the treatment of skin disorders in man has been explored rather extensively. Certainly, skin injury is of lesser consequence than eye damage; however, with the expanding use of higher-power laser systems, the unprotected skin of personnel using lasers may be exposed more frequently to hazardous levels of radiation.

The structural inhomogeneities of the skin cause internal scattering of optical radiation in tissues. As a result there will be multiple internal reflections in addition to absorption and transmission of the incident laser beam. For the common laser sources in the 300–1000 nm range, almost 99% of the radiation penetrating the skin will be absorbed in at least the first 3.6 mm of tissue (see Chapter 1).

For wavelengths greater than 400 nm, the reaction of the skin to absorbed optical radiation is essentially that of a thermal coagulation necrosis. This type of injury can be produced by any optical radiation source of similar parameters and is, therefore, not a reaction specific to laser radiation. It is similar in causation and clinical appearance to the tissue reaction of a deep electrical burn. For pulsed laser irradiations, including exposures in the picosecond domain, there may be other secondary reactions in the tissue. Studies *(6)* have shown that the plume of vaporized tissues or an optical plasma *(20)* produced by high-level irradiation with laser pulses can attenuate a significant portion of the incident energy. This effectively reduces the amount of absorbed radiation in the tissues.

The principal thermal effects of laser exposure depend on the following factors:

— absorption and scattering coefficients of the tissues at the laser wavelength;

— the irradiance or radiant exposure of the laser beam on the tissues;

— the duration of the exposure;

— the extent of the local vascular flow;

— the size of the area irradiated.

As shown in Table 2, the UV spectrum is divided into three specific regions related to the different biological responses of these regions. In the skin, UV-A can cause erythema and hyperpigmentation. In addition to thermal injury caused by UV energy, UV-A and UV-B, probably by acting directly on DNA, may give rise to photocarcinogenesis.

Few data are available on the reaction of skin exposed to UV radiation from highly monochromatic laser sources. It is known, however, that chronic exposure to narrow-band, non-laser UV wavelengths in this range can result in carcinogenic effects on the skin as well as in a severe erythematous and blistering response. On the basis of studies with non-coherent UV radiation, exposure to UV-B is most injurious to human skin; exposure to the shorter UV-C and the longer UV-A wavelengths seems less harmful. The shorter wavelengths are absorbed in the outer, dead layers of the epidermis (stratum corneum) and the longer wavelengths have an initial pigment-darkening effect followed by erythema and delayed pigmentation. It should be remembered that phototoxic and photosensitizing chemicals on the skin may potentiate the effects of lasers operating in the visible and UV regions.

Studies by Mešter et al. *(14–16)* and others on the stimulating effect of low doses of the ruby and helium–neon lasers on hair growth, phagocytosis index and wound healing are of interest in any consideration of chronic effects. Such effects have generally been labelled as biostimulation *(21)*.

Studies *(22–23)* have provided detailed data on the exposure levels required to produce minimal reactions in human skin for six common laser types emitting in the visible and IR regions. The variations, or spread, in the data were found to be directly related to the degree of absorption in the tissues (Table 3).

EXPOSURE LIMITS

To establish a rationale for developing exposure limits (EL) from biological data, a careful analysis is required of the physical and biological variables that influence the spread of laboratory data, the factors related to the potential for injury in individuals exposed, the increase in severity of injury from greater-than-threshold exposures, and the reversibility of injury. In

Table 3. Minimal skin reaction levels[a]

Type of laser	Radiant exposure (kJ/m²)	Exposure duration, *t*
Ruby laser (694.3 nm)		
unpigmented skin	110–200	2.5 ms
pigmented skin	22–69	2.5 ms
Q-switched ruby laser (694.3 nm)	2.5–3.4	75 ns
Argon laser (458–515 nm)	40–82	1 s
Carbon dioxide laser (10.6 μm)	28	1 s
Neodymium glass laser (1060 nm) — Q-switch	25–57	75 ns
Neodymium-YAG laser (1064 nm)	460–780	1 s
Nitrogen (334 nm)	220	210 s

[a] All taken at 50% probability points.

Source: Parrish *(24)*.

addition, the accuracy and availability of measuring instruments and the desire for simplicity in expressing exposure levels influence exposure limits.

The development of adequate and operable EL requires comprehensive evaluation of information obtained from animal experiments and studies on man. Some data may be obtained from volunteers. Surveys of individuals engaged in laser work will give assurance that EL are safe, but may be of limited value in developing standards. The criteria to be used in evaluating experimental results of laser exposure and the interacting variables in such an evaluation require the exercise of informed judgement.

The availability of a broad spectrum of laser sources, although generally advantageous, is a disadvantage when attempting to provide a uniform "all-purpose" laser safety code, as more detailed and specific data are required to establish: *(a)* operational parameters of the lasers in use; *(b)* safe exposure criteria for each laser; and *(c)* protective devices necessary for these lasers. Similarly, those responsible for establishing levels of safe exposure as well as those who manufacture protection devices must also keep pace with advances in technology *(4)*.

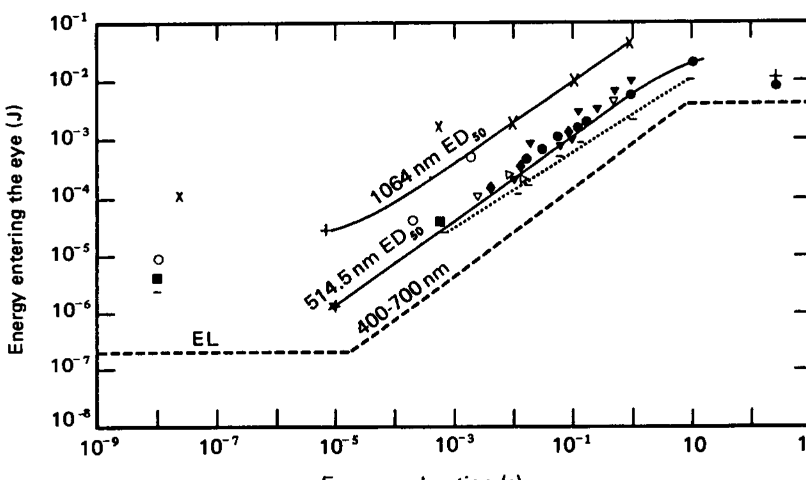
Current protection guides for the eye are based on minimum exposure factors. These threshold values may vary depending on the criteria by which they are measured. In the retina, the criterion is the minimum level required to produce an ophthalmoscopically visible lesion. Other criteria are used for the cornea, lens, etc. The protection guides are based primarily on acute exposure effects, namely thermal injury to the retina, keratitis and dermatological effects. There is only a limited amount of information on long-term effects of chronic exposure of the eye/retina to monochromatic light. Results of recent research suggest a possible loss of small-angle visual acuity following repeated exposure to very low levels of diffusely scattered blue-spectrum laser radiation *(9,12,21)*.

Unfortunately, since the various experiments reported in the literature were not carried out as part of an integrated programme of investigation, there are numerous gaps and inconsistencies in reported results. Such parameters as pulse duration and irradiated spot area or diameter on the retina vary from one study to another.

As mentioned previously, there are at least three principal threshold mechanisms of retinal injury: thermo-acoustic, thermal and photochemical. It is now believed that each mode of injury has a particular temporal relationship or time domain in which it is the principal cause of threshold injuries. Threshold retinal lesions from very short exposures, such as those from mode-locked and Q-switched lasers, probably result in part from a thermo-acoustic transient which accompanies the localized heating in the vicinity of the highly absorbing pigment granules *(25)*. Somewhere in the domain of pulse durations of the order of 1 μs, the acoustic transient no longer plays a significant role and the principal process is that of thermal denaturation of complex organic molecules, although the pigment granules are still localized hot spots *(26,27)*. At ultrashort pulse durations characteristic of mode-locked lasers, optical breakdown can also occur.

Fig. 1 shows the most reliable information from several laboratories for minimum-image-size retinal injury. The two curves represent different

Fig. 1. Laser retinal injury threshold for minimal image condition



Note. Selected data from numerous experiments to determine the laser retinal injury threshold in the rhesus monkey for the minimal image condition. Plotted for comparison is the exposure limited (EL) applicable to intrabeam viewing (minimal image) condition. Data points represent ED_{50} values of Ham et al. *(28)* for helium-neon (▼); Dunsky & Lappin *(29)* for krypton (●); Bresnick et al. *(30)* for argon (▲); Vassiliadis et al. *(31)* for neodymium 530 nm (■), ruby (○); Vassiliadis et al. *(32)* for argon 514.5 nm (◆); Lappin & Coogan *(33)* for helium-neon 632.8 nm (▽); Naidoff & Sliney *(34)* for welding-arc point source (+); Skeen et al. *(35)* for neodymium 1064 nm (x); and Skeen et al. *(36)* for argon 514.5 nm (✱). Points marked (—) indicate lowest reported injury values.

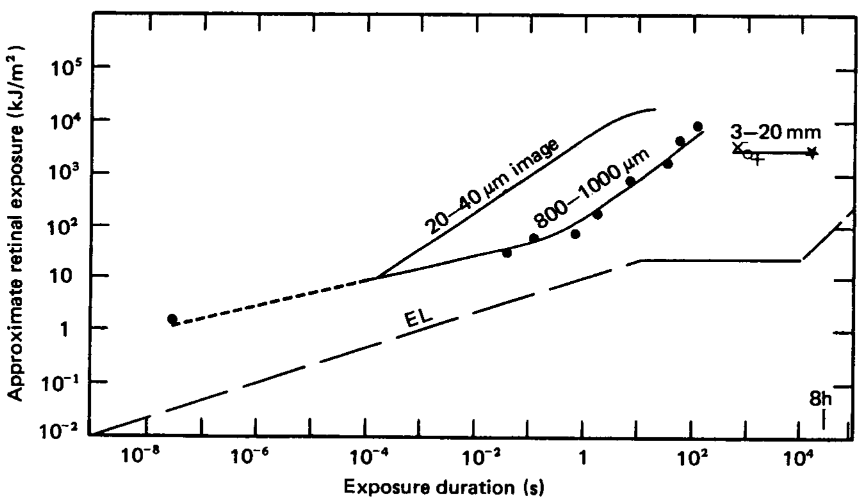
laser wavelengths (514.5 nm and 1064 nm) with exposure durations from about 10 ns to 1000 s. The apparent break in the two curves in the microsecond region indicates the change from the thermo-acoustic to the purely thermal effect. The ocular EL for optical radiation at 514.5 nm is shown for comparison.

A similar display of data for extended sources is shown in Fig. 2. The ocular EL for extended sources and the smoothed threshold for a minimum image size are shown for comparison.

The differences in shape between the threshold curves for the two conditions necessitate different EL curves for each case. In Fig. 3 the basis for the spectral dependence of the EL is shown. The relative absorption by the retina, including the pigment epithelium, is closely approximated by the modification factor (M_A) line. At wavelengths below 450 nm and above 1100 nm the approximation diverges. This divergence is time-dependent and EL are adjusted to follow closely the data points on a wavelength and exposure-duration basis.

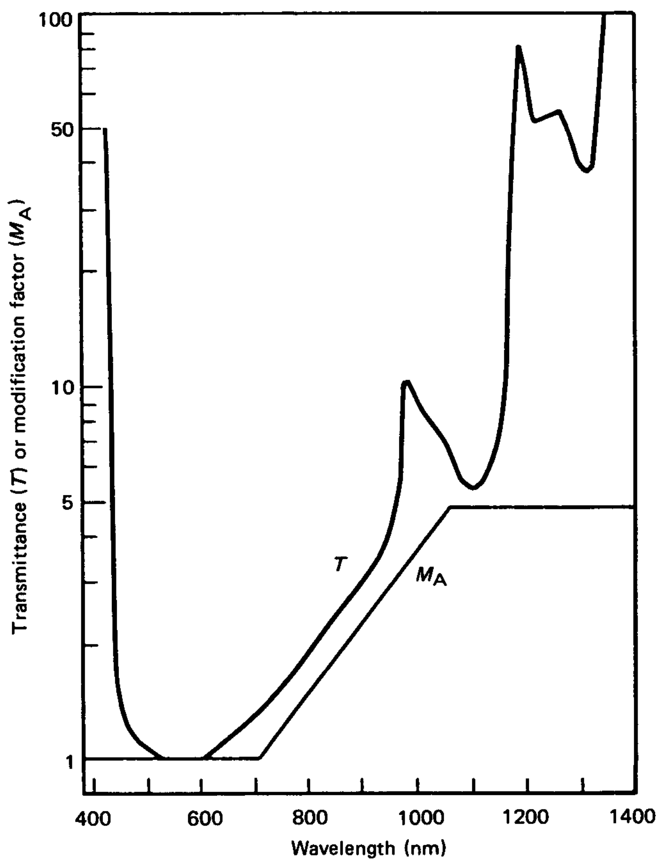
Exposures to visible radiation for durations greater than 1–100 seconds appear to result in injury if EL are much above those encountered in the natural environment. The most sensitive mechanism in this exposure domain appears to be some variety of photochemical reaction to the pigment epithelium. Several mechanisms have been proposed to account for damage

Fig. 2. Laser retinal injury threshold for extended sources



Note. Experimental retinal burn threshold determined by Ham et al. *(37)* in the rabbit for large image sizes, 0.8–1 mm diameter, are shown with long-term exposure data for larger image sizes obtained by Verhoeff & Bell *(38)* (+); Eccles & Flynn *(39)* (○); Kuwabara *(40)* (**X**); and Lawwill *(41)* (✱). The exposure limits (EL) for extended sources and the threshold data curves for small image size at 514.5 nm from Fig. 1 are shown for comparison.

Fig. 3. Relative absorption by the retina and modification factor

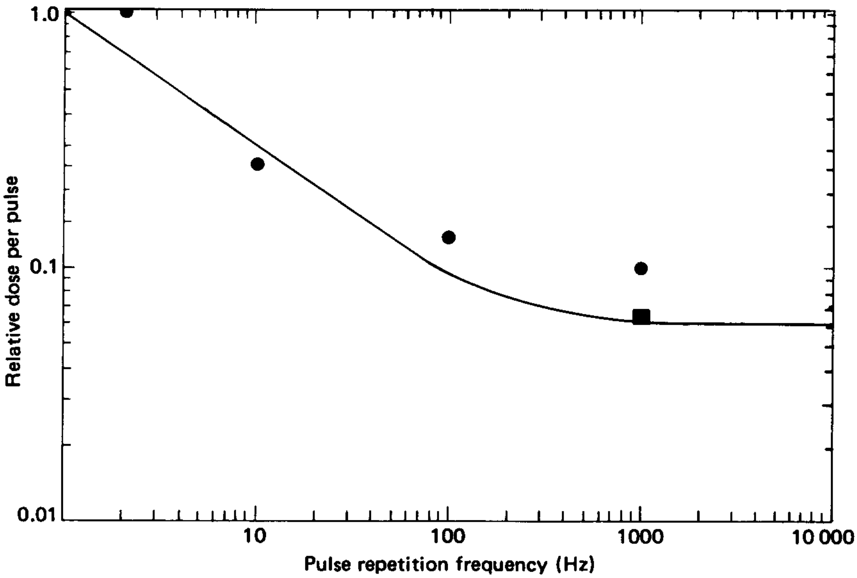


Note. A normalized plot of the reciprocal of the retinal absorption of optical radiation incident on the cornea, based on the data of Geeraets & Berry *(19)* and Boettner *(42)*. The M_A curve used to calculate the EL is shown for comparison. The plateau in the M_A curve from 1050 nm is based on a presumed effect on the ocular lens.

at this level. These are probably interrelated, but the most important appears to be absorption of light by the pigment epithelium or photoreceptor itself. Although ambient retinal temperature is important, it is contributory or synergistic rather than the principal factor *(43–45)*.

Fig. 4 shows the reduction in EL necessitated by the interaction of multiple pulses within a pulse train. The data from later work by Ham (personal communication) validate the continued high level of interaction at frequencies higher than 1000 Hz *(9)*.

Fig. 4. Modification factor for repetitively pulsed lasers having pulse durations shorter than 10^{-5} seconds



Note. The exposure level for a single pulse of the pulse train is multiplied by the above modification factor. The modification factor for a pulse repetition frequency greater than 276 Hz is 0.06. Experimental data: ● — argon; ■ — neodymium.

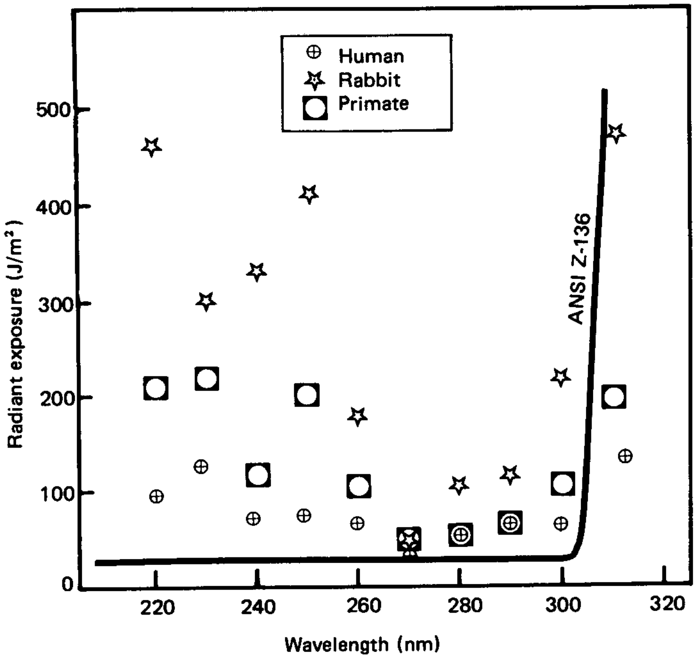
Source: Adapted from IEC *(46)* and Wilkening *(47)*.

The corneal damage levels in the UV are shown in Fig. 5; the EL is the envelope of the human data. It is interesting to note that the non-human primate (monkey) data correlate more closely with the human data than do the rabbit data.

Obviously more data were used as a basis for the EL than those cited above. This information is comprehensively reviewed by Wolbarsht & Sliney *(7)* and Clarke *(51)*. In certain regions, however, few data are available. The situation is discussed later in this chapter and some suggestions concerning the research needed in order to fill the gaps are included in this discussion.

As additional information becomes available the EL will be revised. The development of more or less permanent optical radiation protection standards is thus still not possible. In recent years, however, considerable progress has been made in many countries towards recommended levels. This progress has been greatest for the visible and IR regions, in which many lasers and the xenon arc lamps now operate and where the principal biological data have been collected. The members of the working group that discussed

Fig. 5. Corneal damage levels in the ultraviolet



Note. The UV photokeratitis threshold obtained by Pitts & Gibbons *(48)* for a broad-band (10 nm bandwidth) source is shown in comparison to the EL for UV laser radiation (solid line) *(49)*. The apparent discrepancy in the 303–315 nm range is due to the rapid increase of the biological threshold which could not be adequately tracked using a broad-band source *(50)*.

this chapter felt that, for the most part, the revised scheme of protection standards developed by the American National Standards Institute (ANSI) came closest to meeting the present need for EL. These values have also been adopted by IEC *(46)* and were recommended by the International Non-Ionizing Radiation Committee (INIRC) of the International Radiation Protection Association (IRPA) in 1985 *(52)*, although with some reservations where only a minimal amount of biological data exists and where the limits are based on extrapolation. These limits are listed in Tables 4–7. It is felt that these values are suitable for acute exposures, since the limits were based principally on considerations of immediate and easily assessed effects. However, where photochemical processes are involved (UV exposure of the eye and skin and long-term visible radiation exposure of the eye and skin) the EL should be considered only as guidelines to be used with caution if applied for long-term exposure conditions (i.e. frequently pulsed exposures each day for months or years, or chronic continuous-wave exposure for such periods.

Table 4. Exposure limits for direct ocular exposures (intrabeam viewing) from a laser beam[a]

Wavelength, λ (nm)	Exposure duration, t (s)	Exposure limit, EL	
200– 302		0.03 kJ/m^2	
303		0.04 kJ/m^2	
304		0.06 kJ/m^2	
305		0.10 kJ/m^2	
306		0.16 kJ/m^2	
307		0.25 kJ/m^2	
308	10^{-9}– 3×10^4	0.40 kJ/m^2	Not to exceed $5.6\sqrt[4]{t}$ kJ/m^2
309		0.63 kJ/m^2	
310		1.00 kJ/m^2	
311		1.60 kJ/m^2	
312		2.50 kJ/m^2	
313		4.00 kJ/m^2	
314		6.30 kJ/m^2	
315– 400	10^{-9}– 10	$5.6\sqrt[4]{t}$ kJ/m^2	
315– 400	10 – 10^3	10.0 kJ/m^2	
315– 400	10^3 – 3×10^4	10 W/m^2	
400– 700	10^{-9}–1.8×10^{-5}	0.005 J/m^2	
400– 700	1.8×10^{-5}– 10	$18(t/\sqrt[4]{t})$ J/m^2	
400– 550	10 – 10^4	100 J/m^2	
550– 700	10 – T_1	$18(t/\sqrt[4]{t})$ J/m^2	
550– 700	T_1 – 10^4	$100M_B$ J/m^2	
400– 700	10^4 – 3×10^4	$0.01M_B$ W/m^2	
700–1050	10^{-9}–1.8×10^{-5}	$0.005M_A$ J/m^2	
700–1050	1.8×10^{-5}– 10^3	$18M_A(t/\sqrt[4]{t})$ J/m^2	
1050–1400	10^{-9}– 5×10^{-5}	0.05 J/m^2	
1050–1400	5×10^{-5}– 10^3	$90(t/\sqrt[4]{t})$ J/m^2	
700–1400	10^3 – 3×10^4	$3.2M_A$ W/m^2	
1400– 10^6	10^{-9}– 10^{-7}	100 J/m^2	
1400– 10^6	10^{-7}– 10	$5.6\sqrt[4]{t}$ kJ/m^2	
1400– 10^6	10 – 3×10^4	1 kW/m^2	

[a] The limiting aperture for all EL for wavelengths in the range 100–1000 μm is 10 mm. For all other skin EL and for UV, and for IR-B and IR-C ocular EL, the limiting aperture is 1 mm. For ocular EL in the visible and IR-A region the limiting aperture is 7 mm. Modification factors are: $M_A = 1$ for $\lambda = 400$–700 nm, $M_A = 10^{(0.002(\lambda - 700))}$ for $\lambda = 700$–1050 nm, $M_A = 5$ for $\lambda = 1050$–1400 nm (and see Fig. 3); $M_B = 1$ for $\lambda = 400$–550 nm, $M_B = 10^{(0.015(\lambda - 550))}$ for $\lambda = 550$–700 nm; $T_1 = 10$ seconds for $\lambda = 400$–550 nm, $T_1 = 10 \times 10^{(0.02(\lambda - 550))}$ seconds for $\lambda = 550$–700 nm.

Source: ACGIH *(53)*.

Table 5. Exposure limits for viewing a diffuse reflection of a laser beam or an extended source laser[a]

Wavelength, λ (nm)	Exposure duration, t (s)	Exposure limit, EL
400- 700	10^{-9} - 10	$100\sqrt[3]{t}$ kJ/(m^2•sr)
400- 550	10 - 10^4	210 kJ/(m^2•sr)
550- 700	10 - T_1	$38.3(t\sqrt[4]{T})$ kJ/(m^2•sr)
550- 700	T_1 - 10^4	$210M_B$ kJ/(m^2•sr)
400- 700	10^4 -3 × 10^4	$0.021tM_B$ kW/(m^2•sr)
700-1400	10^{-9} - 10	$100M_A\sqrt[3]{t}$ kJ/(m^2•sr)
700-1400	10 - 10^3	$38.3M_A(t/\sqrt{T})$ kJ/(m^2•sr)
700-1400	10^3 -3 × 10^4	$6.4M_A$ kW/(m^2•sr)

[a] M_A, M_B and T_1 are the same as in the footnote to Table 4.

Source: ACGIH *(53)*.

Table 6. Minimum limiting angle of extended source viewing exposure limits[a]

Exposure duration, t (s)	Angle (mrad)
10^{-9}	8.0
10^{-8}	5.4
10^{-7}	3.7
10^{-6}	2.5
10^{-5}	1.7
10^{-4}	2.2
10^{-3}	3.6
10^{-2}	5.7
10^{-1}	9.2
1.0	15
10	24
10^2	24
10^3	24
10^4	24

[a] For all angles less than limiting angle, use intrabeam viewing exposure limits.

Source: ACGIH *(53)*.

Table 7. Exposure limits for skin exposure from a laser beam[a]

Wavelength, λ (nm)	Exposure duration, t (s)	Exposure limit, EL
200– 400	10^{-9}–3×10^{4}	same as Table 4
400–1400	10^{-9}– 10^{-7}	$0.2M_A$ kJ/m^2
400–1400	10^{-7}– 10	$11M_A\sqrt[4]{t}$ kJ/m^2
400–1400	10 –3×10^{4}	$2M_A$ kW/m^2
1400– 10^{6}	10^{-9}–3×10^{4}	same as Table 4

[a] The limiting aperture for all skin EL for wavelengths in the range 100–1000 μm is 10 mm. For all other skin EL and for UV, and for IR-B and IR-C ocular EL, the limiting aperture is 1 mm. M_A is the same as in the footnote to Table 4.

Source: ACGIH *(53)*, IEC *(46)* and IRPA/INIRC *(52)*.

It should be emphasized that where photochemical injury mechanisms are dominant, the presence of photosensitizers (e.g. drugs, foods, cosmetics) and diseased states or genetic abnormalities may render the EL inapplicable.

HAZARD EVALUATION[a]

General procedures

The applicaton of the EL in evaluating the potential hazard of high-intensity optical sources requires information regarding the use and frequency of exposure. The analysis is largely orientated towards laser sources, but is not restricted to them. The following four aspects of the use of the source influence the total hazard evaluation and thereby determine the application of control measures.

1. The intrinsic capability of the laser or other optical source to injure personnel.

2. The environment in which it will be used.

3. The personnel who operate the hazardous optical source and those who may be exposed.

4. The intended use of the laser or other optical source.

[a] Adapted from ACGIH *(54)*.

The most practical general means for both evaluation and control of laser radiation hazards is to classify the laser systems according to their relative hazards and to draw up specifications for appropriate controls for each class. Reference to the classification scheme in most cases precludes any requirement for radiometric measurements and will generally reduce the need for calculations. In the standardized laser classification scheme, aspect 1 (the potential hazard of the laser or laser system) is defined. Aspects 2 and 3 vary with each laser usage and cannot be readily included in a general classification scheme. Although, in total hazard evaluation procedures, all four aspects must be considered, in most cases aspects 1 and 4 are sufficient to determine the control measures applicable.

Classification of laser device hazards

The hazard classifications specified below are defined by the output parameters and accessible levels of radiation. This classification (Table 8) is based largely on that of the IEC *(46)* the US Food and Drug Administration *(55)* and that used by ANSI *(49)*, with arabic numerals instead of roman. It should be noted that the laser device classification may appear on many commercial laser products manufactured subsequent to the adoption of these standards. It should be used (with conversion of roman numerals to arabic) unless the laser is modified so as to change its output power or energy significantly. The classes are:

1 — laser systems that are not hazardous (non-risk);

2 — laser systems (visible only) that are normally not hazardous by virtue of normal aversion responses (low-risk);

3 — laser systems where intrabeam viewing of the direct beam and specular reflections may be hazardous (moderate-risk), sometimes divided into two subcategories a and b, where class 3a represents a low risk (equivalent to class 2) and is hazardous only if the beam is re-collected by an optical instrument;

4 — laser systems where even diffuse reflections may be hazardous or where the beam produces a fire hazard or serious skin hazard.

The basis of the hazard classification scheme is the ability of the primary laser beam or reflected beam to cause biological damage to the eye or skin.

A class 2 laser or low-power system may be viewed directly under carefully controlled exposure conditions, but must have a cautionary label affixed to the external surface of the device. Similar controls are also required for a class 3a laser.

The moderate-risk class 3b category (or medium-power system) requires control measures to prevent viewing of the direct beam.

Class 4 high-risk (or high-power) systems require the use of controls that prevent exposure of the eye and skin to the direct and diffusely reflected beam. In addition to the possibility of eye damage, exposure to optical radiation from such devices could constitute a serious skin hazard.

Table 8. Laser device classification

Wavelength	Laser classes			
	Non-risk	Low-risk, low- or medium-power	Moderate-risk medium power	High-risk, high-power
Ultraviolet	1	3a	3b	4
Visible	1	2,3a	3b	4
Near-infrared	1	3a	3b	4
Infrared	1	3a	3b	4

Laser output parameters required for hazard classification
Accessible emission limits (AELs) have been established for each class of laser. The following parameters are required for the classification of the different types of laser.

1. Essentially *all* lasers: wavelength(s) or wavelength range, and a determination of the exposure duration.

2. *Continuous-wave* or *repetitively pulsed* lasers: as above, but knowledge of average power output also required.

3. *Pulsed* lasers: as above, but knowledge of total energy/pulse (or peak power), pulse duration, pulse repetition frequency, and emergent beam radiant exposure also required.

4. *Extended-source* laser devices, such as injection laser diodes and those lasers having a permanent diffuser within the output optics: all of the above parameters, but knowledge of the laser source radiance or integrated radiance, and the maximum viewing angular subtense, α, also required.

Definitions of laser device hazard classes

Class 1 — non-risk laser devices
A non-risk laser device is defined as any laser, or laser system containing such a laser, that cannot emit laser radiation levels in excess of the AEL for class 1 (see below) for the classification duration. The exemption from hazard controls applies strictly to emitted laser radiation hazards and not to other potential hazards. The classification duration is the longest daily exposure duration expected.

The AEL for class 1 is defined by a "worst-case" analysis of a laser's potential for producing injury. In this "worst-case" analysis it is necessary to consider not only the laser output irradiance or radiant exposure, but also whether a hazard would exist if the total laser output were concentrated within the defining aperture for the applicable exposure limit. For instance, the unfocused beam of a far-IR continuous-wave laser would normally not be hazardous if the beam irradiance were less than 0.1 W/cm^2; however, if the output power were 10 W and the beam were focused at some location to a spot 1 mm in diameter, a serious hazard could exist. The AELs for class 1 must be defined in two different ways, depending on whether the laser itself is considered an "extended source" (an unusual case).

For most lasers, the AEL for class 1 is the product of $a \times b$, where a is the intrabeam exposure limit for the eye (Table 4) for the exposure duration T_{max} and b is the circular area of the defining aperture for the exposure limit in cm^2.

For extended-source lasers (e.g. laser arrays, laser diodes and diffused-output lasers that emit in the spectral range 400–1400 nm) the AEL for class 1 is determined by a power or energy output such that the source radiance would not exceed the extended source exposure limit (Tables 5 and 6) if the source were viewed at the minimum viewing distance through a theoretically perfect optical viewing system with an entrance aperture of 8 cm which collected the entire laser beam output and which had a 7 mm exit pupil. This AEL is seldom necessary, and the point-source AELs can be applied to provide a conservative analysis.

Class 2 — low-risk, low-power visible laser devices
Low-risk, low-power visible laser devices are defined as follows:

(a) visible continuous-wave laser devices that can emit a power exceeding the AEL for class 1 for the classification duration (0.4 μW for T_{max} greater than 0.25 seconds) but not exceeding 1 mW;

(b) visible scanning laser systems may be evaluated by specifying the AEL for class 1 at a point 10 cm from the exit port of the laser system; these and repetitively pulsed laser devices that can emit a power exceeding the appropriate AEL for class 1 for the classification duration, but not exceeding the AEL for class 1 for a 0.25-second exposure, are low-risk. This AEL can also be referred to as the AEL for class 2.

Any laser device in a low-risk classification by virtue of enclosure must have warning labels indicating "Higher-risk class when access panels are removed". These labels may be covered by a separate enclosure which must be removed before the main access panels can be removed.

Class 3a — low-risk, medium-power laser devices
This class of laser devices is defined as visible-frequency continuous-wave lasers, operating in a power range of 1–5 mW, which have an irradiance in the emergent beam of 25 W/m^2 or less. In some standards the class applies to non-visible frequency lasers within five times the AEL for class 1.

Class 3b — moderate-risk, medium-power laser devices
Moderate-risk, medium-power laser devices are defined as:

(a) UV and IR (1.4μm–1 mm) laser devices that can emit a radiant power in excess of the AEL for the classification duration but cannot emit:

— an average radiation power in excess of 0.5 W for T_{max} greater than 0.25 seconds; or

— a radiant exposure of 100 kJ/m^2 within an exposure duration of 0.25 seconds or less;

(b) visible continuous-wave or repetitively-pulsed laser devices that produce a radiant power in excess of the AEL for class 2 (1 mW for a continuous-wave laser) but cannot emit an average radiant power of 0.5 W for T_{max} greater than 0.25 seconds;

(c) visible and near-IR (400–1400 nm) pulsed laser devices that can emit a radiant energy in excess of the AEL for class 1 but cannot emit a radiant exposure that exceeds either 10 J/cm^2 or that required to produce a hazardous diffuse reflection as given in Table 5;

(d) near-IR (700–1400 nm) continuous-wave or repetitively-pulsed laser devices that can emit power in excess of the AEL for class 1 for the classification duration but cannot emit an average power of 0.5 W or greater for periods in excess of 0.25 seconds.

Class 4 — high-risk, high-power laser devices
High-risk, high-power laser devices are defined as:

(a) UV and IR (1.4μm–1 mm) laser devices that emit an average power in excess of 0.5 W for periods greater than 0.25 seconds, or a radiant exposure of 100 kJ/m^2 within an exposure duration of 0.25 seconds or less;

(b) visible and near-IR (700–1400 nm) laser devices that emit an average power of 0.5 W or more for periods greater than 0.25 seconds, or a radiant exposure in excess of either 100 kJ/m^2 or that radiant exposure output required to produce a hazardous diffuse reflection (3.14 times the radiance values) as given in Table 5.

Classification of multi-wavelength and multiple-source lasers
The classification of laser devices that can potentially emit at numerous wavelengths should be based on the most hazardous possible wavelength combination. Multiple sources are considered independent if separated by the appropriate limiting angle given in Table 6.

Detailed hazard analysis
Classification is the initial step in hazard analysis. However, it is not sufficient merely to classify the laser in terms of its power or energy output; the place and way that a laser is used (or abused) as well as the people who may operate it or be in the exposure zone must also be considered. The additional safety measures that such environmental and personnel factors may require must be taken into account, and are discussed below.

Environment

Environmental factors require careful consideration after the laser device has been classified, as their importance in the total hazard evaluation depends on the laser classification. The decision to employ additional hazard controls not ordinarily required for moderate-risk and high-risk laser devices may depend largely on environmental considerations. The probability of exposure of personnel to hazardous laser radiation must be considered separately since it is influenced by the laser's use: indoors, as in a machine shop, a classroom, a research laboratory, or a factory production line; or outdoors, as in a mine, at a highway construction site, on the open sea, on a military laser range, in the atmosphere above occupied areas, or in a pipeline construction trench. Other environmental hazards should also be considered. If exposure of unprotected personnel to the primary or specularly reflected beam is expected, calculations or measurements of either irradiance or radiant exposure of the primary or specularly reflected beam, or radiance of an extended source, at that specific exposure location are required.

Indoor laser operations

In general only the laser source itself is considered in evaluating an indoor laser operation if the beam is enclosed or is operated in a controlled area. The following step-by-step procedure is recommended for evaluation of moderate-risk laser devices indoors when this is necessary, since unprotected personnel may potentially be exposed with this particular class of laser devices.

Step 1. Determine the applicable AEL considering the maximum exposure duration from the intended use.

Step 2. Determine the hazardous beam path(s).

Step 3. Determine the extent of hazardous specular reflection as indicated in Fig. 6.

Step 4. Determine the extent of hazardous diffuse reflections (nominal hazard zone).

Step 5. Determine whether any non-laser hazards exist.

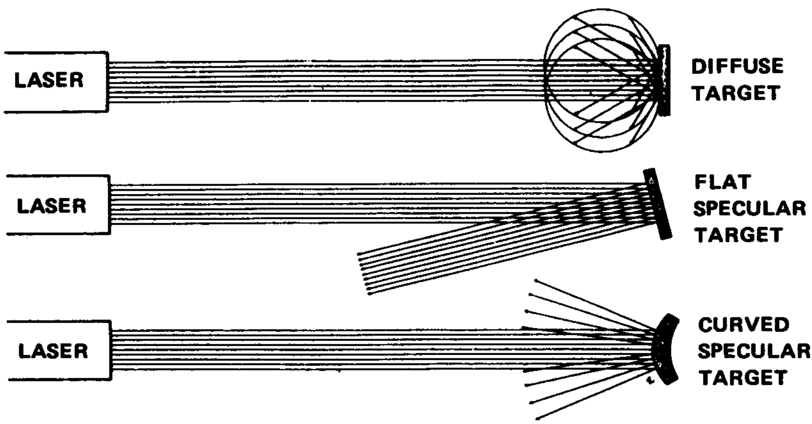
Outdoor laser operations over extended distances

The total hazard evaluation of a particular laser device depends on defining the extent of several potentially hazardous conditions. They may be done in a step-by-step manner as follows.

Step 1. Determine the applicable AEL considering the maximum exposure duration from the intended use.

Step 2. Estimate the nominal hazardous range of the laser.

Fig. 6. Specular reflection of laser beams



Source: ACGIH *(53)*.

Step 3. Evaluate potential hazards from specular-surface reflections, such as those from windows and mirrors in vehicles, and hazards from retroflectors.

Step 4. Determine whether hazardous diffuse reflections exist, especially if the laser is operating in the 400–1400 nm band (nominal hazard zone).

Step 5. Evaluate the stability of the laser platform to determine both the extent of horizontal and vertical range control and which, if any, of the azimuth and elevation constraints need to be placed on the beam traverse.

Step 6. Determine the likelihood of people being present in the area of the laser beam.

Personnel

The individuals who may be in the vicinity of a laser and its emitted beam(s) can influence the decision to adopt additional control measures not specifically required for the class of laser being employed. This again depends on the classification of the laser device.

If children or others unable to read and/or understand warning labels are exposed to potentially hazardous laser radiation, the hazard evaluation is affected and control measures could require appropriate modification.

The type of personnel influences the total hazard evaluation, especially with the use of moderate-risk, medium-power lasers. The principal means of hazard control for certain lasers or laser systems, such as military laser range-finders and some moderate-risk lasers used in the construction industry, is for the operator to keep the laser beam away from personnel or flat, mirror-like surfaces.

The factors to be taken into account with regard to personnel who may be exposed are briefly as follows:

(a) the maturity and general level of training and experience of the laser users (e.g. students, master machinists, soldiers and scientists);

(b) the maturity of onlookers, their awareness that potentially hazardous laser radiation may be present, and their knowledge and ability to apply relevant safety precautions;

(c) the degree of training in laser safety of all individuals involved in laser operation;

(d) the extent to which individuals can be relied on to wear eye protection;

(e) the steps taken to ensure that intentional laser exposures are within the permissible range and that the fail-safe type of attenuator is used when required in the direct beam;

(f) the number and location of individuals relative to the primary beam or reflections, and the probability of accidental exposure.

CONTROL MEASURES

Approaches to laser safety vary greatly among individuals and groups who have an interest in the problem. Most programmes in industry, government and universities are still in course of development. Some organizations have written policies and practices outlining the responsibilities of management and of technical supervision, environmental health, safety and medical personnel. Such policies are usually broadly defined, with specific provisions for individual problems. All such policies and procedures should emphasize the need to rely primarily on appropriate education and training, both of the individual laser operator and of supervisory personnel, for the safe conduct of laser operations; when appropriate, engineering controls rather than personal protective equipment (goggles) should be stressed. Engineering measures should take into account the need for interlocks, proper layout of room areas, shielding materials and warning signs. The criteria for selecting protective eyewear involve many interrelated factors. It should be noted that commercially available protective eyewear is designed for protection against a specific wavelength or group of wavelengths *(47,56,57)*. Eye protection devices designed for protection against specific wavelengths and power from the laser system should be used when engineering and procedural controls are inadequate, so as to eliminate potential exposure in excess of the applicable exposure limit. For cases in which long-term exposure to the eye by visible lasers (only) is not intended, the applicable exposure limit may be based on a 0.25-second duration.

The International Electrotechnical Commission *(46)*, the American Conference of Governmental Industrial Hygienists *(54)* and the Laser Institute of America *(58)* have prepared guides for laser installations, and the American National Standards Institute *(49)* and other national bodies have developed a detailed personnel exposure standard for laser users. These documents give hazard controls for laser radiation that vary depending on the type of laser being used and the manner of its use. The control of laser operation should be entrusted to a knowledgeable laser operator under the supervision of personnel knowledgeable in laser hazards. A closed installation should be used when feasible.

In the above-mentioned guides and standards, only two general precautions are common to all laser installations:

— personnel should not look into the primary beam or at specular reflections of the beam, unless necessary, even if the exposure limit is not exceeded;

— the laser operator should be familiar with the type of laser used and act responsibly.

Fundamental responsibility for laser safety lies with the employing authority. In practice, the employing authority may delegate its responsibility for the establishment and surveillance of appropriate safety measures to a responsible individual. Provision should be made for the appropriate education and training of all individuals using laser devices.

Consideration should be given to the operation of laser devices in a controlled area according to laser classification. Special emphasis should be placed on control of the path of the laser beam. Only authorized personnel should operate laser systems. Spectators should not be allowed to enter a controlled area unless appropriate supervisory approval has been obtained and protective measures taken.

Laser optical systems (mirrors, lenses, beam deflectors, etc.) should be aligned in such a manner that the primary beam, or a specular reflection of the primary beam, cannot result in an ocular exposure above the exposure limit for direct irradiation of the eye.

Optical systems such as lenses, telescopes and microscopes may increase the hazard to the eye when viewing a laser beam, so that special care should be taken in their use. Microscopes and telescopes may be used as optical instruments for viewing, but should be provided with an interlock or filter, if necessary, to prevent ocular exposures above the appropriate exposure limit for irradiation of the eye.

With non-visible laser beams, extra vigilance is necessary to ensure that the beam path is properly positioned and that dangerous specular reflections do not occur. This may entail continuous environmental monitoring.

Laser medical instrumentation for surgery or for diagnostic purposes should have built-in safety devices, including special firing mechanisms, and warning notices as to the need for eye protection and protection of the patient, including the use of non-flammable gas anaesthesia. Safety precautions for any electrical equipment should be included. Laser surgical devices for training purposes should have dual controls. A suitable training programme should be provided for all potential users and operating room personnel. The control measures should not restrict or limit in any way the use of laser radiation of any type that may be intentionally administered to an individual for diagnostic, therapeutic or research purposes, by or under the direction of qualified professionals engaged in the healing arts. Precautions should be taken to ensure that any unnecessary exposure of organs or tissues is minimized.

With the increase in medical and industrial applications of high-power laser systems, there is an increased probability of accidental exposure of the skin to levels of laser radiation above the exposure limit for skin. It is recommended that, for personnel working with such high-power (class 4) laser systems, protection should be provided for the uninvolved skin wherever possible.

Non-laser optical sources

Although lasers pose the greatest potential hazard to the eye and skin among artificial light sources, some arc sources and other high intensity light sources may emit hazardous levels of visible radiation. UV radiation hazards are considered in Chapter 1 and IR radiation hazards in Chapter 3. The exposure limits and protective techniques developed for lasers can be adapted to the evaluation and control of non-laser sources. More sophisticated hazard criteria for evaluating a thermal and photochemical retinal injury hazard have been proposed, but have not been recommended as official standards *(9,53)*.

MEDICAL ASSESSMENT

In the early days of laser use there was a general uncertainty about threshold concepts and associated safe exposure levels. This resulted in a conservative attitude towards possible health problems, and therefore in the widespread adoption of detailed and regular medical surveillance. In the past decade a large volume of empirical data has been collected concerning the possible risks involved in most common laser applications. In addition to threshold studies, the independent evaluation of medical examinations by the members of the WHO Working Group led to the following conclusions:

— it is unlikely that a near-threshold retinal lesion will be identified as such by ophthalmoscopic examination, even if carried out by an ophthalmologist experienced in laser problems;

— most near-threshold laser lesions will not be detected by the exposed individual when the macular region of the retina is unaffected; in most cases it is impossible to differentiate between laser-induced and other retinal lesions and pathologies if more than one week has elapsed since the possible exposure;

— if retinal change is identified, no therapy can be offered;

— if gross damage to the retina, or significant damage to other ocular components has occurred, the exposed individual will be aware of it.

In many countries medical examinations are performed regularly or are at least required for personnel handling laser equipment. In particular, an ophthalmological examination is performed, including tests of visual acuity and visual fields, together with funduscopy and sometimes even fundus photography. It must be realized that the expected ocular changes are often subtle, and that without any clear previous history of a laser hazard an ophthalmologist will have great difficulty in distinguishing an eclipse burn or an early macular degeneration from a laser-induced injury.

From a legal point of view, it will be difficult to relate any ocular or skin change to work with the laser if the hazardous situation cannot be reconstructed in a precise way.

An epidemiological analysis is a very important part of laser hazard evaluation, and an assessment of the individual's health status at the commencement of employment in the laser field is needed as the basis for all future investigations.

In view of the limited amount of information gained from surveillance examinations, and considering the amount of time that has to be devoted to them by highly qualified personnel, it is recommended that skin and eye examinations be carried out on laser workers only when a medical examination is a condition of employment; this requirement has, however, to be waived in the case of class 1 and class 2 lasers. It is also recommended that a medical examination by a qualified expert be carried out immediately after the alleged occurrence of a supra-threshold exposure. Such an examination should be supplemented by a full investigation of the circumstances under which the accident occurred. Results from both these studies should be referred to a central agency and the necessary steps taken to prevent recurrence of similar accidents.

RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

Several laser radiation protection standards and guides have been published *(21,45,49,54,55,58,59)* and exposure limits have been formulated even though several unresolved problems remain with regard to such limits *(7)*.

The present exposure limits are based on all available experimental data. However, detailed information is lacking for certain wavelengths or exposure conditions. The necessary extrapolations in these cases were based on current theories of the mechanism of injury. However, these theories have not been adequately tested.

The main questions remaining concern exposure to laser radiation delivered over extremely short periods (mode-locked lasers) or with exposures delivered at low levels over long periods of time. It appears at present that retinal damage from short pulses is produced by a different mechanism from that producing minimal damage from long exposures. Also, no data are available to show whether interaction between these mechanisms exists, or whether the interaction, if present, is competitive or synergistic. In addition, exposure to UV and IR laser radiation has not been adequately studied, and there are still several large gaps in the available data regarding exposure to repetitive pulse trains of laser radiation. Also, some interesting questions remain with regard to non-circular images, especially when one dimension is small. The line images and elliptical images that may be produced by a laser diode or by a scanning laser are examples of this type of exposure.

All of the known injurious effects are strongly wavelength-dependent. However, little is known about the wavelength relationship in the ultra-short or extremely long time exposure domains. For example, although longer-term exposures to IR radiation result in injury at levels well above present protection standards, the rather sparse data seem to indicate a power-dependent thermal injury mechanism. This is in contrast to the dose-related photochemical model used to predict injury from visible radiation in this time domain. For most exposure durations, injury to the cornea and lens of the eye from UV radiation appears to be photochemical. However, there are indications that occasional thermally enhanced photochemical effects also occur.

Few data are available for long-term (chronic) exposures to laser radiation. Even exposure to non-laser sources, such as bright small-source lamps and high-luminance extended sources, has produced insufficient data to allow extrapolation to laser sources. Thus, the permissible exposure levels were based on the assumption that the total retinal dose from visible illumination levels normally encountered in the natural environment is not hazardous. Recent studies appear to substantiate the theory that injury from chronic low-level exposure is related to absorption by the visual pigment in the photoreceptors. This is particularly true of short-wavelength light *(25)*. However, small temperature rises in the retina (of the order of 2 or 3 °C) appear to synergize with the photochemical process so that melanin pigment absorption will also play a role, albeit a secondary one *(44)*.

The protection standard levels in the far-IR region were based on an understanding of the possible thermal effects of the cornea and a knowledge of exposures that have not resulted in adverse effects on the eye. Because of the lack of accurate data on exposures of the human eye to the IR laser, "worst-case" exposure conditions were assumed. Specifically, it was assumed that absorption takes place in a very thin layer at the anterior surface of the cornea. This condition is best represented by 10.6μm CO_2 laser exposures. For that matter it will, as well, fit exposure of the eye to any wavelength beyond approximately 2.5μm. At wavelengths less than 3μm, the radiation penetrates into the cornea more deeply and significant absorption may take place in the aqueous humour and lens. For these wavelengths, short-term exposure to much greater irradiances can be permitted. However, the risk of IR cataracts is greatest for long-term exposure. The increased interest in certain near-IR lasers, such as hydrogen fluoride, deuterium fluoride, holmium, erbium and neodymium lasers, means that biological investigations to define more detailed permissible exposure conditions in the middle- and near-IR regions, and for long or repeated exposures, will be required.

Only scattered data points are available for damage thresholds to the cornea and lens of the eye from UV radiation. Extrapolations from studies using non-laser UV sources were made in order to arrive at reasonable values. The lack of availability of UV lasers has prevented extensive studies of laser injury thresholds and mechanisms of UV laser injury. Hopefully, the availability in the future of a tunable UV laser with a continuous-wave or nearly continuous output should permit such studies. Meanwhile, those using the present UV standards should consider them only as the best available guidelines. Exposures should be limited as much as possible.

It may legitimately be asked how it is possible to study delayed chronic effects on the retina and other portions of the eye. Will such studies have to be conducted for 20–30 years before we can know what may happen? Many patients who have had laser treatment for eye lesions have now been observed for over 20 years, and have not shown any significant chronic effects in the treated areas or in any adjacent areas as a result of the laser treatment. Fortunately, several powerful research tools are becoming increasingly available that permit study of the ultrastructural changes in tissues soon after exposure. The most valuable of such tools are electron microscopes, both scanning and fixed, and various spectroscopic probes. Studies incorporating such devices should yield a more fundamental understanding of the mechanisms of injury and permit an accurate prediction of chronic effects. As we develop a better understanding of retinal physiology and the fundamental photochemical mechanisms of vision, our predictions of chronic effects will become more reliable.

The interpretation of all such studies requires a sophisticated level of experience. It is important to remember in planning research studies that the availability of acute threshold data does not answer all questions. Clearly, the need exists for further biological studies of laser effects, especially where information is at present lacking. Laser manufacturers and others with lasers of unusual characteristics should be encouraged to make such equipment readily available to institutions conducting laser bioeffects research. In addition, and most importantly, an estimate of the gaps in present knowledge may facilitate a rational approach to future revisions of existing protection standards.

Much of the exposure data now available have been collected in an empirical fashion without any attempt to determine the underlying mechanism(s) of injury. The implications of repeated exposure at low levels below present protection standards cannot be evaluated without a far more complete understanding of the mechanisms of injury. Without such studies there can be no assurance that injurious effects will not appear long after exposure, perhaps many years following active use of lasers. In this regard, study of chronic effects is required since latent ocular effects could ensue from chronic exposure to IR radiation of the lens and anterior portion of the eye. Delayed skin effects might ensue from chronic exposures in the UV and visible frequency ranges; this is of particular importance in the case of individuals who may be photosensitive as a result of drugs or other photosensitizing agents.

For the present, and with due regard to the lack of data in some areas, it is recommended that the maximum permissible exposures of the eye and skin recommended by ANSI Z-136.1 *(49)* be adopted as modified here. It is also recommended that additional studies of the effects of lasers on the skin be performed, especially for acute exposures in the UV spectral region and for chronic exposures over the entire spectral region.

It is felt that there is insufficient information on the effects of chronic exposure to laser radiation. Such information may be obtained through detailed and well controlled epidemiological studies. Such studies should be carried out on limited groups working in a laser environment in which the physical parameters are well defined. Members of these groups should undergo periodic examinations according to a standardized procedure. The studies must include control groups of personnel not exposed to intense optical radiation.

CONCLUSIONS AND RECOMMENDATIONS[a]

Conclusions

Although initially only research workers were exposed to laser radiation, today much of the public is now potentially exposed to lasers used in medicine, communications, entertainment and industry.

For short laser exposures, both peak irradiance (W/m^2) and radiant exposure (J/m^2), as well as the time pattern of exposure, are the important factors determining biological effects. For continuous-wave lasers irradiance is the important factor. In addition to irradiance (dose rate) and radiant exposure (dose), the quantity radiance ($W/(m^2 \cdot sr)$) are useful for calculations of the exposure dose to the retina.

The essential measurements for hazard evaluation should include:

— output level

— divergence

— wavelength

— exposure duration

— pulse repetition frequency

— pulse duration

— beam geometry

— characteristics of any reflecting surfaces.

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[a] These conclusions and recommendations are those pertaining to lasers made by the WHO Working Group on Health Implications of the Increased Use of NIR Technologies and Devices, Ann Arbor, USA, October 1985.

Laser emissions cover wavelengths from 10 nm to 1 mm and are used in a wide variety of applications. The interactions between biological tissues and laser radiation depend on irradiance and radiant exposure, exposure duration and wavelength. The coherence properties of laser radiation *per se* are not considered important.

These interactions can take four main forms: photochemical, thermal, thermo-acoustic, and multiphoton-dependent and non-linear processes such as optical breakdown.

Because of the relatively superficial absorption, the major biological effects are on the skin and the eye. However, because of its unique optical properties, the eye is more vulnerable to injury: visible and IR-A radiation are focused sharply on the retina, and the corneal irradiance may be amplified by as much as 100 000 times.

The health hazards to the skin are both acute (thermal burns, sunburn, photosensitized reactions) and chronic (accelerated aging and photocarcinogenesis). The main health hazards to the eye are photokeratitis, corneal burns, photochemical and thermal cataract, ocular inflammation, and photochemical, thermal and thermo-acoustic retinal injury and optical breakdown within the eye. Secondary haemorrhage in the vitreous humour with complete loss of vision could be produced by severe damage to the retina.

Recommendations

Control measures should include education and training of all personnel working with lasers. Engineering controls, such as proper layout of working areas and enclosure of instruments, should be selected as appropriate. Personal protection may consist of special eyewear and appropriate clothing. Warning signs and other administrative control measures can supplement these measures. Public exposure to hazardous laser radiation should be precluded by the use of laser beam stops and limits on beam paths during laser light shows and outdoor laser use. Applicable control measures are very different depending on the classification of laser equipment: class 1 lasers are totally safe, whereas class 4 lasers are very dangerous and require extreme control measures and precautions.

Several national and international bodies have dealt with the problem of permissible exposure limits. Although there is a lack of data in some areas, there is general agreement on exposure limits such as those recommended by IEC and IRPA. It is also recommended that additional studies of the effects of lasers on the eye and skin be performed, especially for acute exposures in the UV spectral region and for chronic exposures over the entire spectral region.

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