GUIDELINES ON LIMITS OF EXPOSURE TO LASER RADIATION OF WAVELENGTHS BETWEEN 180 nm AND 1,000 μm

International Commission on Non-Ionizing Radiation Protection*

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INTRODUCTION

Lasers are used in a wide variety of industrial, consumer, scientific, and medical applications, including optical fiber communication, compact disc players, alignment, welding, cutting, drilling, heat treatment, distance measurement, entertainment, advertisement, optical computing, and surgery. In most industrial applications the laser radiation is totally enclosed, and even partial enclosures effectively preclude direct human exposure. In some applications, however, for example in research laboratories, laser entertainment displays, and alignment procedures, exposure to potentially hazardous laser radiation is possible, and certain material processing applications use high intensities that can produce sufficient scattered radiation to have adverse health implications.

Additionally, many people are exposed to levels of laser radiation that are not known to produce biological damage, such as those produced by a variety of consumer and office equipment, including video disc players, supermarket scanners, optical communications, facsimile and printing equipment, and guidance devices for the blind. In general, these applications employ low-intensity diode lasers emitting at wavelengths ranging between 630 nm and 910 nm (red light and near-infrared radiation).

Adverse health effects of exposure to laser radiation are theoretically possible across the entire optical spectrum from 180 nm in the ultraviolet (UV) to 10^3 μm in the far infrared (IR), but the risk of retinal injury due to radiation in the visible and near infrared regions (400–1,400 nm) is of particular concern. Exposure limits vary enormously across the optical spectrum because of variations in biological effects and the different structures of the eye that are potentially at risk; the limits developed for this wavelength region are for exposure durations between 1 ns and 8 h (30 ks). The biological effects induced by optical radiation are essentially the same for both coherent and incoherent sources for any given wavelength, exposure site and area, and duration. Laser radiation, however, must be treated as a special case because few conventional optical sources can produce the radiant exposures and irradiances achieved by lasers.

In 1982, under the joint sponsorship of the United Nations Environment Programme, the World Health Organization, and the International Radiation Protection Association, a review was published of the reported biological effects of exposure to optical radiation from lasers and other sources (UNEP/WHO/IRPA 1982). Although further biological data have been published since that time, the basic findings and conclusions of that review are still current and served as the scientific rationale for the development of these guidelines.

The present guidelines on limits of exposure to laser radiation update and supersede those previously published by the Commission's predecessor organization, the IRPA/International Non-Ionizing Radiation Committee (IRPA/INIRC 1985, 1988; Duchêne et al. 1991). Changes have been made to the recommended exposure limits to provide a more accurate hazard criterion for extended-source ocular exposures as well as for infrared exposures of the eye and the skin; these changes apply specifically to optically aided magnified viewing, which produces large retinal images. To simplify and unify the laser safety criteria, only one set of ocular exposure limits is provided for point-source viewing and diffuse reflection or extended-source viewing.

In establishing exposure limits, the Commission recognizes the need to reconcile a number of differing expert opinions. The validity of scientific reports has to be considered, and extrapolations from animal experiments to effects on humans have to be made. The exposure limits in these guidelines were based on scientific data alone, and no consideration was given to economic impact or other non-scientific priorities. All currently available knowledge, however, indicates that these limits will provide an adequate level of protection

* At the 8th International Congress of the International Radiation Protection Association (Montreal, 18–22 May 1992), the IRPA established a new independent scientific organization, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), as a continuation of the former IRPA/International Non-Ionizing Radiation Committee (IRPA/INIRC). The functions of the Commission are to investigate non-ionizing radiation (NIR) hazards, develop international guidelines on exposure limits to NIR and to deal with all aspects of NIR protection. ICNIRP Secretariat, c/o Dipl.-Ing. R. Matthes, Bundesamt für Strahlenschutz, Institut für Strahlenhygiene, Ingolstädter Landstraße 1, D-85764 Oberschleißheim, Germany.

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against known laser effects under all normal exposure conditions. Where no data were available for certain wavelength regions, exposure limits were based on the biological effects of exposure to conventional optical sources, and larger safety factors were applied. The degree of uncertainty inherent in deriving biological thresholds for broad-band and monochromatic sources has frequently prompted the use of additional safety factors in the exposure limits for laser radiation, and this is particularly the case in the UV range.

During the preparation of these guidelines, the composition of the Commission was as follows: M.H. Repacholi, Chairman (Australia); M. Grandolfo, Vice-Chairman (Italy); U. Bergqvist (Sweden); J.H. Bernhardt (Germany); J.P. Césarini (France); L.A. Court (France); A.F. McKinlay (UK); D.H. Sliney (USA); J.A.J. Stolwijk (USA); M.L. Swicord (USA); L.D. Szabo (Hungary); T.S. Tenforde (USA); H.P. Jammet (Chairman-emeritus, France); R. Matthes, Scientific Secretary (Germany); A.S. Duchêne, Scientific Editor (France, now retired).

The IRPA Associate Societies, as well as a number of competent institutions and individual experts, were also consulted, and their cooperation is gratefully acknowledged.

PURPOSE AND SCOPE

The purpose of these guidelines is to establish the basic principles of protection against optical radiation emitted by lasers. They are intended as guidance for experts and national and international bodies who are responsible for developing regulations, recommendations, or codes of practice to protect workers and the general public from the potentially adverse effects of laser radiation.

The exposure limits listed apply to wavelengths from 180 nm to 10^3 μm (1 mm) and are based on an international consensus on the health effects and hazards of laser radiation (UNEP/WHO/IRPA 1982). The guidelines apply to all human exposure, both acute and chronic, to optical radiation emitted by lasers, with the exception of deliberate exposure as an integral part of medical treatment. Any medical exposure above the recommended limit could result in permanent damage to health, and risk/benefit analysis is essential in such circumstances. Anaesthesia may cause different sensitivity to laser radiation. In general, however, diagnostic procedures should not exceed the exposure limits.

QUANTITIES AND UNITS

Exposure limits for optical radiation are expressed using the following quantities and units. *Irradiance* (E) expressed in W m^{-2}, mW cm^{-2}, or μW cm^{-2}, and *radiant exposure* (H), expressed in J m^{-2}, mJ cm^{-2}, or μJ cm^{-2}, are used in describing the concepts of surface exposure dose rate and surface exposure dose from direct exposure to laser radiation. *Radiance* (L), expressed in W m^{-2} sr^{-1} or W cm^{-2} sr^{-1}, and *time-integrated radiance* (Lp), expressed in J m^{-2} sr^{-1} or J cm^{-2} sr^{-1}, are used to describe the "brightness" of an extended source that gives rise to an image on the retina. Other radiometric quantities such as *fluence rate* and *fluence*, although similarly expressed in W m^{-2} and J m^{-2}, respectively, should not be used; the fundamental definitions are different and employ the concept of additive backscatter.

RATIONALE FOR THE EXPOSURE LIMITS

The eye and skin are the organs most susceptible to damage by laser radiation. The type of effect, injury thresholds, and damage mechanisms vary significantly with wavelength, and approximately as the spectral regions shown in Table 1, defined by the International Commission on Illumination (CIE). These spectral bands have been used as the basis for specifying the exposure limits, although the predominant adverse biological effects are much less sharply defined and exhibit a degree of overlap. The consequences of overexposure of the eye are generally more serious than those of overexposure of the skin, and safety standards have therefore emphasized protection of the eye (UNEP/WHO/IRPA 1982; Suess and Benwell-Morison 1989; ACGIH 1990; Duchêne et al. 1991; ANSI 1993; IEC 1993).

BIOLOGICAL EFFECTS

Mechanisms of interaction with biological tissue

Laser biological effects are the result of one or more competing biophysical interaction mechanisms—thermal, acoustic, optical (electric breakdown), and photochemical—which vary depending upon spectral region and exposure duration. For example, in the 400–1,400 nm band, thermal injury to the retina resulting from temperature elevation in the pigmented epithelium is the principal effect for exposure durations less than 10 s, and superficial thermal injury to the cornea and skin occurs at wavelengths greater than 1,400 nm. Thermoacoustic injury occurs at pulse durations less than approximately 0.1 ms and can lead, for example, to haemorrhagic lesions of the retina from Q-switched lasers. Optical breakdown and plasma formation become important only

Table 1. Divisions of the optical spectrum.

Band	Wavelength	Other terminology
UVC	100 nm to 280 nm	Far ultraviolet
UVB	280 nm to 315 nm	Middle ultraviolet
UVA	315 nm to 400 nm	Near ultraviolet
Light	400 nm to 780 nm	Visible
IRA	780 nm to 1400 nm	Near infrared
IRB	1.4 μm to 3 μm	Middle infrared
IRC	3 μm to 10^3 μm	Far infrared

Note: These ranges are in accordance with those defined by the International Commission on Illumination (CIE). In addition, while there is no sharp boundary between the visible and UV wavelengths, the boundaries commonly used are given in this Table.

Table 2. Intrabeam laser ocular exposure limits.[a]

Wavelength, λ (nm)	Exposure duration, t	Exposure limit	Restrictions
Ultraviolet			
180–302	1 ns to 30 ks	3.0×10^1 J m^{-2}	
303	1 ns to 30 ks	4.0×10^1 J m^{-2}	
304	1 ns to 30 ks	6.0×10^1 J m^{-2}	
305	1 ns to 30 ks	1.0×10^2 J m^{-2}	
306	1 ns to 30 ks	1.6×10^2 J m^{-2}	
307	1 ns to 30 ks	2.5×10^2 J m^{-2}	
308	1 ns to 30 ks	4.0×10^2 J m^{-2}	All exposure limits for λ < 315 nm must be $\le 5.6 \times 10^3 t^{1/4}$ J m^{-2} for $t < 10$ s
309	1 ns to 30 ks	6.3×10^2 J m^{-2}	
310	1 ns to 30 ks	1.0×10^3 J m^{-2}	
311	1 ns to 30 ks	1.6×10^3 J m^{-2}	
312	1 ns to 30 ks	2.5×10^3 J m^{-2}	
313	1 ns to 30 ks	4.0×10^3 J m^{-2}	
314	1 ns to 30 ks	6.3×10^3 J m^{-2}	
315–400	1 ns to 10 s	$5.6 \times 10^3 t^{1/4}$ J m^{-2}	
315–400	10 s to 30 ks	1.0×10^4 J m^{-2}	
Visible and IRA			
400–700	1 ns to 18 μs	0.005 J m^{-2}	
400–700	18 μs to 10 s	$18t^{3/4}$ J m^{-2}	
400–550	10 s to 10 ks	100 J m^{-2}	
550–700	10 s to T_1	$18t^{3/4}$ J m^{-2}	
550–700	T_1 to 10 ks	$100C_B$ J m^{-2}	
400–700	10 ks to 30 ks	$0.01C_B$ W m^{-2}	
700–1050	1 ns to 18 μs	0.005 C_A J m^{-2}	
700–1050	18 μs to 1 ks	18 $C_A t^{3/4}$ J m^{-2}	
1051–1400	1 ns to 50 μs	0.05 C_C J m^{-2}	
1,051–1,400	50 μs to 1 ks	$90C_C t^{3/4}$ J m^{-2}	
701–1,400	1 ks to 30 ks	$3.2C_A C_C$ W m^{-2}	
IRB and IRC			
1,401–1,500	1 ns to 1.0 ms	1,000 J m^{-2}	
1,401–1,500	1.0 ms to 10 s	5,600 $t^{1/4}$ J m^{-2}	
1,501–1,800	1 ns to 10 s	10^4 J m^{-2}	
1,801–2,600	1 ns to 1.0 ms	1,000 J m^{-2}	
1,801–2,600	1.0 ms to 10 s	$5{,}600t^{1/4}$ J m^{-2}	
2,601–10^6	1 ns to 100 ns	100 J m^{-2}	
2,601–10^6	100 ns to 10 s	$5{,}600t^{1/4}$ J m^{-2}	
1,401–10^6	10 s to 30 ks	1,000 W m^{-2}	

[a] See Table 5 for aperture sizes.

Note: 1 ks = 1,000 s; 30 ks = 8 h; $C_A = 1$ if $\lambda = 400$–700 nm; $C_A = 10^{[0.002(\lambda - 700)]}$ if $\lambda = 700$–1,050 nm; $C_A = 5$ if $\lambda = 1{,}051$–1,400 nm; $C_B = 1$ if $\lambda < 550$ nm; $C_B = 10^{[0.015(\lambda - 550)]}$ if $\lambda = 550$–700 nm; $T_1 = 10 \times 10^{[0.02(\lambda - 550)]}$ s if $\lambda = 550$–700 nm; and $C_c = 1$ if $\lambda < 1{,}150$; $C_c = 10^{0.0181(\lambda - 1150)}$ if $1{,}150 < \lambda < 1{,}200$; $C_c = 8$ if $1{,}200 < \lambda < 1{,}400$.

from sub-nanosecond exposures. Photochemical injury predominates in the UV spectral region and is also the principal type of injury resulting from lengthy exposures (10 s or more) to short-wavelength visible radiation (principally "blue light").

Effects of UV radiation

Short-wavelength UVB and UVC radiation is absorbed within the cornea and conjunctiva, whereas UVA radiation is absorbed largely in the lens (UNEP/WHO/IRPA 1982). Exposure to "actinic" UV (UVB and UVC) laser radiation may produce the acute effects of erythema (reddening of the skin), photokeratitis (corneal inflammation), and conjunctivitis. Typically, 1,000-fold greater intensities or durations of UVA exposure are required to produce photokeratitis and erythema by a photochemical mechanism. Thermal injury to the skin or the lens and cornea from UVA exposure has been demonstrated for short pulse durations but has not been demonstrated experimentally for UVA exposure durations greater than 1 ms (UNEP/WHO/IRPA 1982). With longer exposures, photochemical effects dominate. For photokeratitis, peak sensitivity is believed to be around 270 nm, with a decrease in the action spectrum in each direction. The peak of the erythemal action spectrum varies from 200 to 300 nm depending upon the definition of the degree of severity and the time of assessment of the effect. In the actinic-UV region, the cornea is not substantially more sensitive to injury than untanned lightly pigmented skin, but corneal damage is much more disabling (and painful). Repeated exposure of the skin results in tanning and thickening of the stratum corneum, which provides increased natural protection; the same is not true of the cornea. Although there is greater absorption of UVA than of UVB in the lens, it now seems likely that cataract formation is primarily due to excessive UVB exposure. In the aphakic eye UV wavelengths greater than 300 nm reach the retina and can cause photochemical injury (Ham et al. 1982).

Effects of visible and IRA radiation

The primary effect on the eye of visible and IRA radiation (400–1,400 nm) is damage to the retina. Because of the transparency of the ocular media and—in particular—the inherent focusing properties of the eye, the retina is much more susceptible to damage by radiation in this spectral region than any other part of the body. For a point source of light or for intrabeam viewing, the optical gain in irradiance from the cornea to retina is approximately 100,000. Most of the radiation that reaches the retina is absorbed by the pigmented epithelium and the underlying choroid (which supplies blood to much of the retina) (Geeraets and Berry 1968; Vassiliadis 1971; Birngruber 1978). The reciprocal of the retinal absorption is illustrated in Fig. 1. The photopigments in the retina absorb only a small fraction of the incident radiation—perhaps less than 15%. Injury to the skin in this spectral region results from temperature rises exceeding 45 °C; photosensitization of the skin to visible light is rare, but can happen.

Recent studies appear to substantiate the photochemical theory that injury from chronic low-level exposure is related to absorption by the retinal pigmented epithelium and choroid of short-wavelength light in the 400–520 nm region (Ham et al. 1976). However, small temperature rises in the retina (of the order of 2–3 °C)

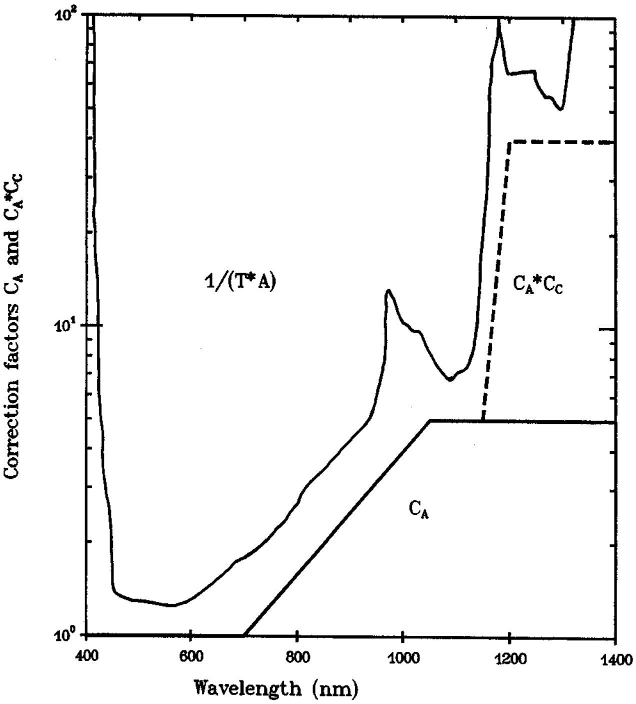

Fig. 1. Retinal absorption and the spectral weighting factors C_A and C_c. The upper curve is the reciprocal of the retinal absorption A and transmittance T of the ocular media. It may also be thought of as the reciprocal of the action spectrum for retinal thermal injury as measured at the cornea. A more useful spectral weighting factor, C_A, is the lower function composed of straight-line segments to approximate ($1/TA$) between 400 and 1,150 nm and $C_A C_C$ which approximates ($1/TA$) for longer wavelengths.

appear to be synergistic with the photochemical process so that absorption by melanin over a broad wavelength band will also play a role, albeit secondary. Visible radiation of shorter wavelength has also been alleged to aggravate retinal aging (Komarova et al. 1978; Marshall 1978), although there appears to be more than one action spectrum for photochemical damage from lengthy exposures (Noell 1980; Kremers and Van Norren 1988).

Data are available for the radiation thresholds at which biological effects become manifest, and the mechanisms of retinal injury as a function of retinal image size (i.e., both for minimal-spot-size, intrabeam viewing and for extended sources) in the wavelength region 400–1,400 nm are understood. Although there are no definite boundaries between injury mechanisms, certain mechanisms dominate according to the exposure duration at threshold. For short-duration exposures (less than a few seconds) the damage is due to thermal injury. Q-switched pulses lasting of the order of 10 ns will also cause mechanical disruption at levels somewhat higher than the threshold for simple thermal coagulation of tissue. Photochemical, rather than thermal, effects predominate only in the wavelength region from 400 nm to approximately 550–700 nm for lengthy exposure times (more than 10 s). At IRA wavelengths where the photochemical effect apparently disappears, thermal effects still dominate for exposure times in excess of 10 s. Radial heat flow produces a strong dependence of retinal injury threshold on retinal image size (Courant et al. 1989b). At short wavelengths in the visible spectrum, eye movements become an important factor for exposure times greater than about 0.1–10 s, and photochemical injury of the retina also becomes dependent on spot size (Sliney 1988, 1989).

Effects of infrared (IRB and IRC) radiation

In the IRB and IRC regions of the spectrum (wavelengths greater than 1.4 μm), the ocular media are opaque because of absorption of the radiation by the water component. Thus, in these infrared regions, radiation causes damage primarily to the cornea, although lens damage has also been attributed to wavelengths below 3 μm (IRA and IRB). The IR damage mechanism appears to be thermal, at least for exposure durations greater than 1 μs; for pulses of shorter duration the mechanism may be thermomechanical. The CO_2 laser (10.6 μm), the Nd:YAG laser (1.06 μm), and the holmium laser (12.1 μm) that are now used in surgical applications are typical of IR radiation sources that cause thermal injury to tissue. In the IRC region, as in the UV, the exposure threshold for damage to the skin is comparable with that for damage to the cornea. However, damage to the cornea is likely to be of greater concern because of the adverse impact on vision.

DERIVATION OF EXPOSURE LIMITS

Extensive studies on the biological effects of laser radiation were used to establish a rationale for exposure limits. The derivation of exposure limits required a careful analysis of the physical and biological variables that most affected reported laboratory biological data, including individual susceptibility, the increase in severity of injury for supra-threshold exposure dose, the possibility of unknown narrow-band absorptions in biological molecules, the effect of eye movements, the actual mechanisms of injury, and the reversibility of damage. Additional considerations were the accuracy of available radiometric instruments and the desire for simplicity in expressing the exposure limits. The relative impact of each of these factors varies with wavelength and exposure duration (ACGIH 1990).

SAFETY FACTORS

It is not possible to define a single "safety factor" between the threshold of injury and the exposure limit; in each derivation a probit analysis was applied. General principles of risk analysis governed the determination of safety factors, and whenever quantitative information—such as probit curves—was available, it was used. An exposure value resulting in a 50% probability for an observed effect (ED-50) has the greatest statistical reliability and was therefore used in comparing reports from different laboratories. Comparisons showed excellent inter-laboratory agreement when exposure conditions were the same. Evidence of injury (observed by light and electron microscopy) was always found at exposure values below the ED-50 derived by ophthalmic examination. Microscopic injuries never appeared at exposures less than one-tenth of the ED-50 and usually appeared at between 25 and 50% of the ED-50. Generally an order of magnitude factor between the ED-50 and the exposure limit was thought to provide an adequate margin of protection against significant or subjectively detectable acute injury. Derived by principles of risk analysis, safety factors were generally largest where fewest experimental data were available. The purpose of incorporating a safety factor into exposure limits is to preclude acute injury or minor effects that could potentially give rise to delayed effects (Sliney 1989). Revisions of exposure limits for extended sources were prompted by concern about both the wide variation and the inadequacy of the safety factor (Courant et al. 1989a).

Spectral considerations: ultraviolet radiation

Lasers that emit in the UV region are still relatively uncommon, although this situation is rapidly changing with the introduction of excimer lasers. UV lasers are used almost exclusively in research laboratories, eye surgery, and micro-applications in material processing. The exposure limits for UV lasers are very similar to those for non-laser UV radiation, and are based on the same biological data. Because of the uncertainty regarding the actual action spectra for photo-keratitis and lenticular cataractogenesis between 300 and 315 nm, slightly more conservative exposure limits for UVB lasers than for non-laser sources were thought desirable. When these guidelines were published, no data were available on threshold biological effects for monochromatic UVB laser radiation; however, some UVA laser photokeratitis thresholds are known and were considered (Wolbarsht and Sliney 1974; Zuclich and Connolly 1976). Recently determined thresholds for photokeratitis show that there is an enormous safety factor of more than 100 for 193-nm UVC laser radiation (Sliney and Marshall 1991). For a more detailed discussion of UV health hazards, the reader is referred to the rationale for the IRPA Guidelines on Limits of Exposure to Ultraviolet Radiation (Duchêne et al. 1991).

Spectral considerations: visible and near infrared

Injury thresholds for both the cornea and the retina vary considerably with wavelength, and it is therefore necessary to consider the precision required to track this variation. It seems acceptable to adjust the exposure limits for different wavelengths, but in a simpler manner than the biological data might indicate. Exposure limits for wavelengths between 700 and 1,050 nm increase with wavelength by a factor C_A; C_A increases from 1 to 5 as the wavelength increases from 700 to 1,050 nm as shown in Fig. 1. Between 1,050 and 1,400 nm, exposure limits for both eye and skin include a constant spectral correction factor C_A of 5 and, for ocular exposure to ultra-short pulses, an additional factor of 2. The reciprocal of the retinal absorption relative to corneal irradiances, shown in Fig. 1, is an indication of the relative effectiveness of different wavelengths in causing retinal injury (UNEP/WHO/IRPA 1982).

As a result of a joint meeting of experts from ICNIRP, ACGIH, IEC, and ANSI at Aberdeen, Maryland, in 1992, a consensus was reached to introduce a new correction factor C_C for the IR limits. This was based on a review of the appropriate scientific literature and the realization of the large safety factors existing for exposure limits in this spectral region (ACGIH 1993; ANSI 1993; IEC 1993). Thus a new correction factor, C_C, is introduced in this revision, with values in the range from 1 to 8. The factor accounts for the greatly decreased retinal hazard at wavelengths greater than 1,100 nm; C_C results from the increased absorption of energy in the ocular media. The curve in Fig. 1 does not consider the relative hazard to the lens of the eye in the near IR, which had to be taken into account before limits at this end of the IRA spectral region were relaxed. Studies show that the correction factor can increase greatly in the IRA (Lund et al. 1981, 1988). Because of the abrupt onset of transmission of the ocular media at about 400 nm, the strong reabsorption at 1,400 nm, and the shift of injury mechanisms at wavelengths from about 550 to 700 nm, some discontinuities exist at 400, 700, and 1,400 nm.

At ocular exposure durations exceeding 10 s, short-wavelength visible radiation causes photochemical retinal injury. The difference between the ocular exposure limits for short (less than 550 nm) and longer (550–700 nm) visible wavelengths therefore increases with greater exposure durations up to 10,000 s. Another wavelength correction factor, C_B, is used to adjust for this change in retinal sensitivity with wavelength. Applying C_B at wavelengths between 550 and 700 nm leads to greater exposure limit values at these longer visible wavelengths for exposure durations exceeding 10 s. Values of C_B are given in Fig. 2.

Spectral considerations: middle and far infrared

Exposure limits for the far-infrared region were based on an understanding of the possible thermal effects on the cornea and a knowledge of exposures that have caused no adverse ocular effects. Because of the lack of accurate data available in 1985 and 1988 for exposures of the human eye to infrared laser radiation, worst-case exposure conditions were assumed. Specifically, it was then assumed that absorption occurred only in a very thin layer at the anterior surface of the cornea. This condition is epitomized by exposure to laser radiation at 3 μm and at 10.6 μm (CO_2 lasers), and also applies to exposures of the eye to any wavelength beyond approximately 3 μm. At wavelengths less than 3 μm the radiation penetrates more deeply into the cornea, and significant absorption may take place in the aqueous humour and even the lens (Avdeev et al. 1978; Wolbarsht 1978; Stuck et al. 1981; McCally et al. 1992); this effect has led to the changes incorporated in these guidelines.

Spectral correction factors for wavelengths between 1.4 and 3 μm are built into the ocular exposure limits for IR laser radiation, based on the varying depth of penetration into the cornea and aqueous humour (Stuck et al. 1981). Insufficient data are available (compared with the extensive database at 10.6 μm) to allow additional wavelength corrections to be defined over the entire IR range. No further extrapolation to other wavelengths is justified on the basis of information currently available.

The changes made in this revision to the exposure limit tables, as well as to the factors in the notes to the tables, were based on more recent biological research, accident experience, and clinical experience from a large increase in the use of IRA and IRB lasers. Exposure limits for the mid-infrared region were altered by increasing limits in the 1.4–2.6 μm spectral band. Prior to this revision, concern had been expressed that there was only one step function at a single wavelength in the 1.4–2.6 μm spectral band (i.e., a 100-fold increase over exposure limits for pulsed far-infrared at 1,540 nm). A more gradual transition and intermediate step functions were added in the 1.4–1.5 μm and 1.8–2.6 μm bands. These increased exposure limits are based on biological threshold data that vary markedly with wavelength for pulsed (but not continuous wave) lasers (Lund et al. 1981; Stuck et al. 1981).

Although it has been suggested that it would be desirable to have smooth transitions in the 1.3–1.5 μm band and around 1.8 μm and beyond, this would have required substantially more calculations on the part of the user of the exposure limits. In the past, there have been objections to this approach in other spectral bands; the Commission was reluctant to continue the practice of step functions, but considered it to be more important to retain a simple set of values that could be read from a table.

For continuous wave lasers, exposure limits could not be increased in the IRB spectral range, but a limiting aperture of 3.5 mm, rather than 1 mm, was found to be justified for hazard evaluation throughout the IRB and IRC regions. This led to a review of the spot-size dependence of corneal injury and the size of safety factors in the exposure limits for pulsed and continuous wave infrared lasers. The choice of the 3.5 mm aperture required a number of compromises, since the biological threshold varies continuously with both spot size and exposure duration. The data of McCally et al. (1992) was useful in the review of the revised exposure limit, and thermal burn data at 1.54, 2.06, 2.7–3.2, and 10.6 μm (Lund et al. 1981; Stuck et al. 1981) showed that enormous safety factors had previously existed. It should be noted that a safety factor of about 2 exists for corneal exposure in the 250–320 nm UV band and a factor of 5–10 for much of the retinal effect of exposure to visible radiation (Sliney and Wolbarsht 1980; Sliney 1989).

Despite the fact that IR corneal injury is a purely thermal effect, that the cornea is resilient to injury, and that corneal epithelium undergoes quick repair, all standards and guidelines have historically provided a much larger safety factor in the IRB and IRC regions. This large factor arose initially because there were no available data, except from CO_2 laser research, on which to base exposure limits. At 10.6 μm, where threshold values are lower than 1.4–2.6 μm for continuous wave lasers (Bargeron et al. 1989; McCally et al. 1992), the 10-s threshold for a 1-mm diameter beam is 9–10 W cm^{-2}, giving a safety factor of 100 for the exposure limit (0.1 W cm^{-2}). For a 3.5-mm beam the threshold is 3–4 W cm^{-2} (safety factor of 30–40), and for a beam of diameter more than 8 mm the threshold drops to about 2 W cm^{-2} (safety factor of 20). Thus, even if all the power entering the 0.096 cm^2 area of a 3.5-mm aperture at the recommended exposure limit of 0.1 W cm^{-2} (i.e. 9.6 mW) were focused on a 1-mm corneal spot, the irradiance would be 1.2 W cm^{-2}, which corresponds to a safety factor of about 8 below burn threshold. This safety factor remains larger than in other spectral regions. Furthermore, a hazardous ocular exposure to continuous wave laser radiation for a period as long as 10 s is also unrealistic, since the eye will move somewhat even if an individual is "stationary"; if exposures approached 0.1 W cm^{-2} for a second or two, there would be an almost immediate sense of heating of the cornea, leading to blinking and rotation of the eye. The infrared corneal aversion response is a subject that requires further study before user safety requirements are relaxed, but the extreme rarity of infrared laser corneal injuries in the workplace clearly suggests that this response may provide significant protection.

Studies of bioeffect thresholds for other IR wavelengths are continuing at several laboratories (McCally et al. 1992), and the resulting data may permit the derivation of smoother, more gradual exposure limit curves in the future, and perhaps an elimination of the step functions and unnecessarily large safety factors in the middle infrared (IRB).

Multiple wavelengths

When laser exposures occur at several different wavelengths and certain exposure intervals, present theories cannot reliably predict the effects of interaction. It would be surprising if there were no interaction and if each injury mechanism acted independently of the others. For practical purposes, and in the absence of clear data, the exposures are considered to be additive where the same tissue (e.g., the cornea) is the site of absorption for multiple wavelengths (Wolbarsht and Sliney 1974; Lyon 1985).

Extremes of exposure duration

All of the known injurious effects of laser radiation have a strong wavelength dependence, which is especially important for long-term exposures. However, little has been established about the relationship to wavelength of ultra-short (<1 ns) or extremely long (several hours) exposures (Goldman et al. 1977; Kremers and Van Norren 1988; Roach et al. 1994).

Repetitive-pulse exposure. One of the most difficult problems in developing the exposure limits concerns repetitive-pulse exposure when the duration of individual pulses is less than 10 μs. Although there are extensive data on biological thresholds, the formulae for determining the exposure limit for a train of pulses remain empirical since present theories of thermal retinal injury do not adequately predict the pulse additivity that is actually seen. Nevertheless, the empirical data for repetitive-pulse thermal injury following a relationship proportional to the number of pulses N raised to the negative ¼-power has been shown to apply to both cornea and retina and for values of N up to and exceeding 10^6 (Ham et al. 1988; Griess et al. 1980; Sliney and Marshall 1991).

Chronic exposure. The exposure limits were derived to preclude the development of delayed effects. Without an adequate understanding of the mechanisms of injury, there can be no certainty that injurious effects will not appear long after exposure to laser radiation at levels below the reported acute thresholds—perhaps many years later. Limited data are available for repeated, long-term (chronic) exposures to laser radiation. Ocular effects are by far the most important type of injury, and delayed ocular effects may well be caused by chronic exposure of the lens and anterior portion of the eye to UVB and IRA radiation, and perhaps to UVA as well. A substantial effort has therefore been made to elucidate the injury mechanism(s) underlying each biological effect in order to judge the possibility of delayed effects. Several environmental epidemiological studies of solar retinitis, UV cataract, and skin cancer have aided assessment of the likelihood of delayed effects (IARC 1992). Epidemiological studies of infrared cataract by Lydahl (1984) have been of particular importance with regard to chronic exposure of the eye to infrared radiation. The exposure limits for very long exposures were based on levels found in more moderate outdoor environments where people have adapted their dress and social customs to limit the likelihood of delayed effects on the eye and skin (Sliney and Wolbarsht 1980; Sliney 1989). In practice, intrabeam laser exposures greater than 100 s rarely occurs unless from ophthalmic instruments.

Point sources and extended sources

For wavelengths between 400 and 1,400 nm—the "retinal hazard region"—the ocular exposure limit depends upon the viewing condition. In physiological optics it is customary to distinguish between a "point source" and an "extended source"; in the context of laser safety, however, exact geometrical definitions are not possible. Small sources often fall into the "point source" category because of retinal heat flow and eye movements which distribute the focal energy over larger retinal areas for increasing exposure durations. "Extended source" conditions apply to sources that subtend a visual angle at the eye greater than "alpha-min" (α_{min}), which has a value of 1.5 mrad for pulsed lasers. Because of eye movements, α_{min} varies with exposure durations greater than 0.7 s (as used in Fig. 7). Exposure limits for large extended sources at angles greater than 0.1 rad can be described with different units, i.e., as radiance (W m^{-2} sr^{-1}) and integrated radiance (J m^{-2} sr^{-1}). The quantities of irradiance (W m^{-2}) and radiant exposure (J m^{-2}) are used for point-source exposure limits, and may also be used for smaller extended sources with angular subtense α<0.1 rad (i.e., <5.7°). Since both photochemical and thermal injury may be caused by both small and large retinal images, the revision of extended source limits required careful consideration of the relative contribution of these two effects.

For any extended source, the angle subtended by a circular source at distance r is termed "alpha" (α). The angle α of a source is the linear angle subtending a solid angle at the eye equal to the quotient of the extended source diameter (or the mean of the shortest and longest dimensions of a non-circular source, when the exposure limit is expressed in J m^{-2} or W m^{-2}) and the viewing distance r. The angle α should not be confused with the beam divergence of the laser.

Large retinal spot sizes. For direct intrabeam viewing, the retinal image may be only about 10–20 μm in diameter; for viewing diffuse laser reflections, however, the image may be much larger (Bergqvist et al. 1978; Cleuet and Mayer 1980; Sliney and Wolbarsht 1980). Initially, there were two sets of ocular exposure limits in this spectral range, for point and extended sources. This approach has been changed by the introduction of a correction factor C_E, which simply increases the point-source exposure limits and retains the radiometric quantity of irradiance or radiant exposure.

Most laser sources are effectively "point sources," i.e., they will not produce an extended image on the retina if the emitted wavelength is between 400 and 1,400 nm. In a few cases, however, as when viewing a diffuse reflection, some laser diode arrays, or a diffused laser source, extended-source conditions prevail. Refinement—and consequent simplification—in the computation of the hazards of extended-source viewing now allows more precise analysis of those hazards. Limits applicable to extended sources are now based on the intrabeam viewing limits modified by a correction factor C_E which applies between the values of α_{min} and α_{max}:

$$C_E = 1.0 \text{ for } \alpha \leq \alpha_{min}; \quad \text{and} \tag{1}$$

$$C_E = \alpha/\alpha_{min} \text{ for } \alpha_{min} < \alpha \leq \alpha_{max}. \tag{2}$$

Maximum and minimum angular subtense (α_{max} and α_{min}). The time-dependent factor of α_{min} of a source distinguishes between point-source and extended-source viewing. The value of α_{min} increases with time to allow for the reduced hazard that results from involuntary eye movements and behavioral reactions such as movement of the head.

The revised exposure limits for extended sources allow a linear increase in the exposure limit measured at the cornea based on the diameter of the retinal image for laser sources subtending an angle between α_{min} and α_{max}. This contrasts with earlier exposure limits, which were expressed as dual limits for intrabeam viewing (effective point sources) and for viewing sources that produce very large retinal images. Previously exposure limits for these very large images (greater than 24 mrad for exposure durations in excess of 10 s) were expressed in terms of radiance or integrated radiance.

Retinal irradiance or radiant exposure is directly proportional to source radiance or integrated radiance. This means that the energy entering the eye when an extended source is viewed increases as the square of the diameter, d_r, of the retinal image. Courant and Sliney have shown that a linear dependence more closely follows the limited biological data, at least for source angles less than 100 mrad (Sliney 1988; Courant et al. 1989a, 1989b). Thermal injury dominates, and because of heat dissipation by choroidal blood flow, among other factors, the image-size dependence begins to fail around 1 mm. For this reason, and on the basis of experience with individuals viewing large incoherent light sources at very close range, the 1994 revision applies only up to an α_{max} of 0.1 rad (retinal image size 1.7 mm). Thermal model calculations were used to justify the α^2 dependence of retinal injury thresholds for larger image sizes where α exceeded 0.1 rad.

Other factors that were considered in revising the exposure limits for extended sources were the effect of eye movements and the minimal image size (intrabeam, diverging beam, or point-source viewing) at which dependence of the threshold on $1/d_r$ begins. A 3.5-mrad value was initially proposed for α_{min} by Courant et al. (1989a), but it was later determined that a value of 1.5 mrad (i.e. a 24-μm minimal image on the retina) best fitted the biological data in their paper. Data from eye movement studies (Yarbus 1967; Sliney and Wolbarsht 1980) and from retinal burn accidents caused by welding arcs (minimum image size conditions) support a value of 11 mrad (i.e., $d_r \approx 200$ μm retinal irradiated zone size) for retinal exposures in excess of 10 s. A smooth transition between these two values of α was therefore derived between 0.7 s and 10 s; the $t^{3/4}$ function was needed to maintain a constant retinal radiant exposure during the transition in α_{min}. The revised limit therefore defines the difference between viewing a point (or minimal) source (intrabeam viewing of a true geometrical point source or a very small source) and viewing an extended source in terms of α_{min}. The new definition of α_{min} is as follows:

$$\alpha_{min} = 1.5 \text{ mrad for } t < 0.7 \text{ s}; \tag{3}$$

$$\alpha_{min} = 2 \cdot t^{3/4} \text{ mrad for } 0.7 \text{ s} \leq t < 10 \text{ s; and} \tag{4}$$

$$\alpha_{min} = 11 \text{ mrad for } t \geq 10 \text{ s}. \tag{5}$$

The exposure limits for extended sources that have an angular source dimension exceeding α_{min} are then derived by multiplying the point-source exposure limits by a correction factor C_E. This factor is applicable provided that the angular subtense α of the source is greater than α_{min} and less than 0.1 rad (i.e., 100 mrad = α_{max}). If the visual angle α subtending the source exceeds 0.1 rad (i.e. $\alpha > \alpha_{max} = 100$ mrad), the exposure limits increase as the square of the angular subtense or, for greater angles, can be expressed as a constant radiance. Indeed, for lengthy viewing times (>100 s), only the radiance exposure limits for α_{max} should be applied unless the eye is immobilized or exposed by an ophthalmic instrument.

Outside the retinal hazard region, source size is not important and only one set of exposure limits is necessary for the eye; these are expressed as irradiances or radiant exposures. The angle of incidence of a laser beam on the eye and skin can be important in assessment of the actual health risk, since incident rays perpendicular to the absorbing tissue are reflected the least and are therefore most dangerous. However, this factor was not specifically treated in the derivation of the exposure limits (Bergqvist et al. 1978), which were derived for worst-case absorbing conditions. Measurement procedures can account for this where needed by using a cosine-response detector and limited field-of-view for the viewing conditions of interest.

Defining apertures

One of the problems in developing an exposure limit for any form of optical radiation is the specification of the limiting aperture over which the level must be measured or calculated. For the skin, where no focusing takes place, it is desirable to use a relatively small aperture. Unfortunately, several difficulties arise from the use of small apertures: more time is required to assess exposure, a more sensitive instrument is required, calibration problems give rise to potential inaccuracies, and calculations may be more difficult (Le Bodo 1976;

Rocherolles 1978; Sliney and Wolbarsht 1980). A 1-mm aperture is about the smallest practical size for averaging of irradiance and is biologically supportable because of scattering in tissue; hence a 1-mm aperture is used for pulsed exposure of the cornea and conjunctiva to UV radiation and to IR radiation of wavelength greater than 1.4 μm. An aperture of at least 3.5 mm was deemed justifiable for both pulsed and continuous exposure of the skin, where increased scattering takes place and the safety factor need not be as great as that for the eye. A still larger aperture can be justified for lengthy exposures greater than 100 s. Moreover, for continuous exposure conditions of the eye (as well as the skin), heat flow and body movements, as well as scattering, tend to eliminate any adverse effects of "hot spots" smaller than about 3.5 mm (Rockwell and Goldman 1974; Sliney and Wolbarsht 1980; McCally et al. 1992; ANSI 1993; IEC 1993). The same arguments hold for continuous exposure of the cornea and conjunctiva to UV radiation at wavelengths less than 400 nm. Furthermore, two factors that account for localized variations in beam irradiances—atmospherically induced "hot spots" and the mode structure in multimode lasers—seldom account for significantly higher localized beam irradiances within areas less than 3.5 mm in diameter.

In the development of laser product performance (emission) safety standards, a single aperture diameter of either 50 mm (assumed to simulate viewing by binoculars at distances greater than 2–3 m) or 7 mm (at a 100–200 mm distance given for the near-point of the eye, or for use of magnifying lenses) has often been specified for simplicity; however, this is possible only because of special exposure conditions in standards (IEC 1993; U.S. FDA 1994). Another problem appears at far infrared wavelengths greater than 100 μm, at which the aperture size of 1 mm begins to create significant diffraction effects and calibration becomes difficult. Fortunately, "hot spots" must, because of the laws of physics, be generally larger than at shorter wavelengths, and aperture diameters of about 11 mm (an area of about 1 cm^2) are therefore specified for wavelengths greater than 100 μm.

For exposure of the human eye within the retinal hazard region (400–1,400 nm) the pupillary aperture "averages" the radiant exposure, and a 7-mm aperture—corresponding to a dark-adapted (dilated) pupil—is standardized. Although the pupil may be smaller, the risk does not decrease proportionally with decreased pupillary area when a point source is viewed (Sliney 1971): the minimal retinal image diameter increases with increasing pupil diameter. Only for extended-source viewing could a case be made for increasing exposure limits for smaller pupil sizes. However, the possible use of certain medications that dilate the pupil argues against a sliding scale of exposure limits for bright ambient conditions.

General Skin exposure

Radial heat flow away from an absorbing area and strong scattering in the stratum corneum and epidermis also influence skin injury thresholds, and this (along with a smaller safety factor for very small spots) is taken into account with the aperture size (3.5 mm) used for measurement of exposures. Concerns about heat stress impose restrictions on exposure of large skin surfaces. At wavelengths greater than 1.4 μm, for beam cross-sectional areas of 0.01–0.1 m^2, the exposure limit for durations exceeding 10 s is $10/A_s$ W m^{-2}, where A_s is the area of the exposed skin in m^2. For exposed skin areas exceeding 0.1 m^2, the exposure limit is 100 W m^{-2}.

Exposure limits for the skin also increase by the spectral correction factor (C_A) given in Fig. 1, for wavelengths between 700 and 1,400 nm. This should not imply that skin exposure limits were derived from ocular exposure data, but since both retinal and skin thresholds vary inversely with melanin absorption in this spectral region, the same correction factor C_A can be used. Likewise, the varying penetration depths in the IRB allow for the same variations in limits for pulsed lasers as apply for the eye.

EXPOSURE LIMITS

The exposure limits for eye and skin are provided in Tables 2, 3, and 4; the values listed are to be used as given for the indicated wavelength ranges for single exposures. For multiple or repetitively pulsed exposures, an additional correction factor, C_P, must be applied to the exposure limit. Moreover, exposure limits for the eye are always specified at a plane tangential to the cornea at the point of the optical axis of the eye; for skin, exposure limits are specified at the skin surface. Spectral correction factors, including C_A, C_B, and C_C, are already incorporated in Tables 2–4.

Figs. 3, 4, and 5 may be used in determining exposure limits for durations that require calculations of fractional powers. The following clarifications should be read before tables and figures are used to determine the correct exposure limit (Figs. 6, 7, and 8).

EXTENDED-SOURCE EXPOSURE LIMITS

In assessing potential laser hazards to the eye, only the intrabeam exposure limits in Table 2 need normally be considered. However, extended-source exposure limits are provided in Table 3 for special situations. The point-source intrabeam exposure limits in Table 2 may be applied in all cases, but may provide too conservative a result. The extended-source correction factor C_E increases the exposure limit in Table 2—applicable to the point source—to indicate more accurately the real risk of injury to the retina.

Exposure duration

Determining the exposure limit applicable for a specific laser exposure requires a determination of the wavelength and the exposure duration. For a single-pulse exposure, this duration is obvious; however, the following criteria should be applied where repeated exposures or lengthy exposures occur.

Table 3. Extended-source laser ocular exposure limits for λ = 400–1400 nm.

Extended-source exposure limits apply to the spectral region between 400 and 1,400 nm. Outside this retinal hazard region, source size is not important and only one set of exposure limits is necessary for the eye. These extended-source exposure limits are expressed as either (A) irradiances or radiant exposures for angle $\alpha < 0.1$ rad or (B) radiances or integrated radiances for greater angles.

A. Small extended sources with angular subtense less than 0.1 radian

The exposure limits for extended sources with subtended angle α greater than α_{min} and less than α_{max} are determined by multiplying the appropriate intrabeam exposure limits in Table 2 by an extended-source correction factor C_E, where

$$C_E = 1.0 \text{ for } \alpha \leq \alpha_{min};$$

$$C_E = \alpha/\alpha_{min} \text{ for } \alpha_{min} < \alpha \leq \alpha_{max};$$

and the angular subtense, α, of the source, where

$$\alpha_{min} = 1.5\text{mrad for } t < 0.7 \text{ s};$$

$$\alpha_{min} = 2t^{3/4}\text{mrad for } 0.7 \text{ s} \leq t < 10 \text{ s};$$

$$\alpha_{min} = 11 \text{ mrad for } t \geq 10 \text{ s};$$

$$\alpha_{max} = 100 \text{ mrad for all values of t}.$$

Therefore, expressed specifically,

$$C_E = (\alpha/1.5 \text{ mrad}) \text{ for all exposure durations of } t < 0.7 \text{ s};$$

$$C_E = [\alpha/(2t^{3/4})\text{mrad}] \text{ for exposure durations of } 0.7 \text{ s} \leq t < 10\text{s}; \textit{ and}$$

$$C_E = (\alpha/11 \text{ mrad}) \text{ for exposure durations of t} \geq 10 \text{ s}.$$

B. Large extended sources with angular subtense greater than 0.1 radian

If the visual angle α subtending the source is greater than 0.1 rad (i.e. $\alpha > \alpha_{max} = 100$ mrad), the integrated radiance or radiance L_{EL} shall not exceed

$$L_{EL}=(8.5\times10^3)\times(EL_{\text{pt source}}) \text{ J m}^{-2} \text{ sr}^{-1} \text{ for } t < 0.7 \text{ s};$$

$$L_{EL}=(6.4\times10^3 t^{4/3}) \times (EL_{\text{pt source}}) \text{ J m}^{-2} \text{ sr}^{-1} \text{ for } 0.7 \text{ s} \leq t < 10 \text{ s; and}$$

$$L_{EL}=(1.16\times10^3)\times(EL_{\text{pt source}}) \text{ J m}^{-2} \text{ sr}^{-1} \text{ (or W m}^{-2} \text{ sr}^{-1} \text{ as applicable) for t} \geq 10 \text{ s}.$$

Alternatively, the value of C_E for $\alpha > 0.1$ rad could be calculated with $C_E = \alpha^2/(\alpha_{min} \cdot \alpha_{max})$ for the exposure limit expressed in J m^{-2}.

Table 4. Laser radiation exposure limits for the skin.

Wavelength, λ (nm)	Exposure duration, t	Exposure limit	Restrictions
Ultraviolet			
180–400	1 ns to 30 ks	As for eye	
Visible and IRA			
400–1,400	1 ns to 100 ns	$0.2C_A$ kJ m^{-2}	See Table 5
400–1,400	100 ns to 10 s	$11\ C_A t^{1/4}$ kJ m^{-2}	for limiting
400–1,400	10 s to 30 ks	$2.0C_A$ kW m^{-2}	apertures
Far infrared			
1,401–10^6	1 ns to 30 ks	As for eye[a]	

[a] For exposed skin areas greater than 0.1 m^2, the exposure limit is reduced to 100 W m^{-2}. For exposed areas between 0.01 and 0.1 m^2, the exposure limit is inversely proportional to the exposed area.
Note: 1 ks = 1,000 s; 30 ks = 8 h; and
$C_A = 1$ if λ = 400–700 nm; $C_A = 10^{[0.002(\lambda - 700)]}$ if λ = 700–1,050 nm; $C_A = 5$ if λ = 1,051–1,400 nm.

For any single-pulse laser exposure, the exposure duration is the pulse duration, t, defined at the half-peak-power points of the pulse. For all skin exposure limits, and for ocular exposure to non-visible or barely visible wavelengths (less than 400 nm or greater than 700 nm), the exposure duration for continuous wave lasers is the maximum anticipated time, T_{max}, of direct exposure. For exposure of the eye to any continuous wave laser, the exposure duration is the maximum anticipated time of direct viewing. However, if purposeful staring into a visible (400–700 nm) beam is not intended or anticipated, the aversion response time, 0.25 s, should be used. Aside from deliberate exposure from ophthalmic instrument sources, deliberate staring at a bright source effectively never occurs. For ocular exposures in the near-infrared (700–1,400 nm), a maximum exposure duration of 10 s provides an adequate hazard criterion for either unintended or purposeful viewing conditions. In this case, eye movements will provide a natural exposure limitation and thus eliminate the need to consider exposure durations greater than 10 s, except for unusual conditions. In special applications, such as intentional exposure from medical instrumentation for diagnostic purposes, even longer exposure durations may apply.

Exposure limits for pulse durations less than 1 ns cannot be provided at present because of a lack of biological data; however, a conservative interim guideline would be to limit peak irradiances to the exposure limit applicable to nanosecond pulses at the wavelength of interest for durations between 0.01 - 1.0 ns.

Repetitive laser exposures

Within any one day, repeated exposure to laser radiation can be the result of multiple exposures to a beam from a continuous wave laser or of exposures to repetitively pulsed lasers and some scanning beam lasers. Scanning beams create repetitive-pulse exposures of the eye in the retinal hazard region (400–1,400 nm). Both the individual pulse duration and the total cumulative exposure duration must be determined. Total exposure duration of the train of pulses is determined in the same manner as for continuous wave exposures—that is, time, T, from the beginning of the exposure (first pulse) to the end (last pulse). The methods for determining the exposure limits for repetitive laser exposures are as follows:

- *Repeated exposures, UV (315–400 nm) laser radiation:* The exposure dose is additive over a 24-h period, regardless of the repetition rate. The exposure limit for any 24-h period should be reduced by a factor of 2.5 relative to the single-pulse limit if, on succeeding days, exposures near the limit are expected.
- *Repeated ocular exposures, visible (400–700 nm) and infrared (>700 nm to 10^3 μm) for both scanned continuous wave lasers and repetitively pulsed exposure conditions:* The exposure limit per pulse for repetitively pulsed intrabeam viewing must be reduced by a correction factor C_P, equal to $N^{-1/4}$, applied to the exposure limit for a single pulse of the same duration (t), where N, the number of pulses, is the product of the pulse repetition frequency and the total exposure duration (T). The duration T is determined in the same manner as for a continuous wave laser of the same wavelength (see "Exposure duration" above). This exposure limit applies to all wavelengths greater than 700 nm (thermal injury). For wavelengths less than 700 nm, where photochemical damage mechanisms may also apply, the exposure limit corrected using C_P must also not exceed the limit calculated for Nt seconds when t is the duration of a single pulse in the train and Nt is greater than 10 s. It can be shown that, for pulse repetition frequencies greater than 15 kHz for wavelengths of 400–1,050 nm, or greater than 20 kHz for wavelengths of 1,050–1,400 nm, the average irradiance or radiant exposure (radiance or integrated radiance) of the pulse train will not exceed the exposure limit for a continuous wave exposure for the viewing duration T of 10 s. Average irradiance is the total radiant exposure delivered during time T, divided by T.
- *Repeated exposure of the skin:* For repetitive-pulse laser exposure of the skin, the exposure limit based on a single-pulse exposure should not be exceeded, and the average irradiance of the pulse train should not exceed the exposure limit applicable for the total duration T of the pulse train as given in Table 4.

An example of how the exposure limit tables should be used is given in the Appendix.

Special precautions

1. These exposure limits apply to the general population; it should be recognized, however, that some rare photosensitive individuals may react to UV laser exposures below these limits. Such individuals should therefore take more rigorous precautions to avoid exposure to UV laser radiation. In addition, the exposure limits from 300 to 400 nm do not apply to infants or to aphakic individuals.
2. These exposure limits are not intended to limit use of lasers as an integral and essential part of medical treatment.

MEASUREMENT

Limiting apertures and field-of-view for calculation and measurement

Radiant exposures or irradiances measured or calculated for comparison with these guidelines may be averaged over one of the three principal circular apertures with a receptor having a cosine response within the specified field-of-view. At wavelengths outside the retinal hazard spectral region (400–1,400 nm), these are as follows: a 1-mm diameter aperture for pulsed exposure

Table 5. Limiting apertures for applying the exposure limits.

Spectral region	Exposure duration, t (s)	Eye exposure (mm)	Skin exposure (mm)
180–400 nm	<10 s	1.0	3.5
	≥10 s	3.5	3.5
400–1,400 nm	1 ns to 30 ks	7.0	3.5
1,401–10^5 nm	1 ns to 0.3 s	1.0	3.5
	0.3 to 10 s	$1.5t^{3/8}$	3.5
	10 s to 30 ks	3.5	3.5
10^5–10^6 nm	1 ns to 30 ks	11.0	11.0

of the eye, a 3.5-mm diameter aperture for all continuous wave exposures of the eye, and a 3.5-mm aperture for pulsed and 7 mm for continuous wave exposures (>10 s) of the skin. For exposure durations between 0.3 and 10 s and comparison with the ocular exposure limits for infrared wavelengths between 1.4 and 10^2 μm, there is a variable aperture function given in Table 5. For comparison with the ocular exposure limits in the retinal hazard spectral range between 400 and 1,400 nm, the measurements should be made using a detector with a 7-mm limiting aperture (pupil) with a receptor field-of-view of at least α_{min} for point sources and α or α_{max} for extended sources (see "Point sources and extended sources" above). An exception to this applies for comparison with all exposure limits for wavelengths between 10^2 and 10^3 μm, where the limiting aperture is 11 mm with a receptor having a cosine response. No modifications of the exposure limits are permitted for reduced energy entering an assumed pupil size less than 7 mm.

When a laser source is diffused by reflection from a scattering target or by a translucent material, the source brightness is not normally dangerous and does not require hazard evaluation. However, for those rare instances involving a Q-switched visible or near infrared laser of very high peak power, it may be necessary to introduce a correction factor C_E for analyzing the potential hazard of viewing the extended source. In all cases the "point-source" exposure limits may be applied but may be excessively conservative. The extended source correction factor increases the exposure limit applicable to the point source to indicate more accurately the real risk of injury to the retina. Laser diode arrays may also be extended sources if viewed at very close distances. **It is important to recognize that almost all hazardous ocular exposure conditions occur for intrabeam, point-source conditions.** Only with extremely high peak-power, Q-switched laser reflections from a diffuse target is it likely that extended-source viewing conditions exceeding the extended-source exposure limits will be encountered.

Detailed measurement procedures or calculation methods are beyond the scope of this document. Suffice it to say that many potential sources of error exist in laser radiation measurement, and measurement of irradiance, radiant exposure, and radiance should not be attempted without a thorough knowledge of laser radiometry (Le Bodo 1976; Bergqvist et al. 1978; Sliney and Wolbarsht 1980; Lyon 1993a, b).

PROTECTIVE MEASURES

The most effective means of controlling laser hazards is total enclosure of the laser and all beam paths. For conditions where this not possible, partial beam enclosure, laser eye protectors, restricted access to beam paths, and administrative controls may be necessary. Laser safety standards and guidelines have been developed worldwide that make use of a hazard classification scheme to permit specification of control measures based on the risk posed by the laser. In some laser operations, control measures are also necessary for electrical and fire hazards, x rays, noise, and airborne contaminants (these are generally encountered only with class 4 laser systems).

CONCLUDING REMARKS

Although laser technology is relatively new, extensive research into the bioeffects of laser radiation has been conducted during the past 30 years. The results of this research, combined with knowledge of the effects of

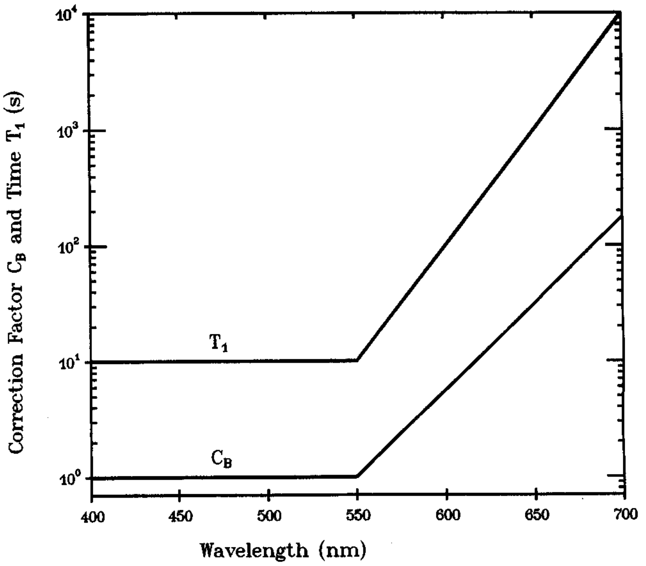

Fig. 2. Exposure limit correction factor C_B and time T_1 used in Table 2 are applied when calculating limits for continuous wave or repetitively pulsed laser exposures of durations greater than 10 s in the visible wavelength range.

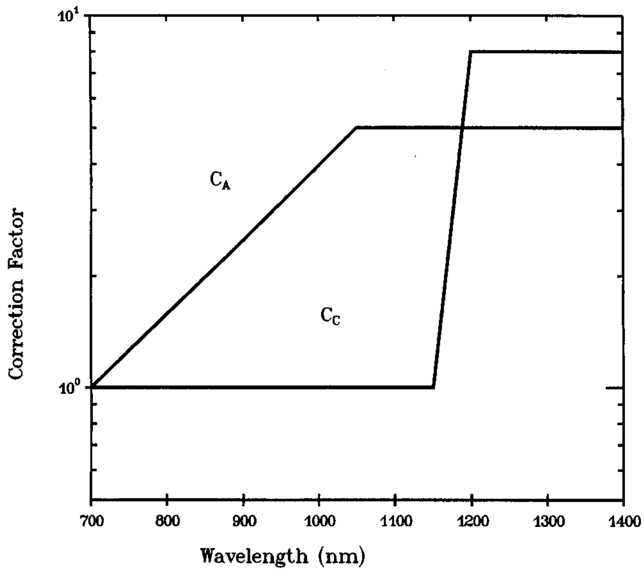

Fig. 3. Spectral correction factors C_A and C_C are used to calculate near-infrared laser exposure limits (Tables 2 and 4).

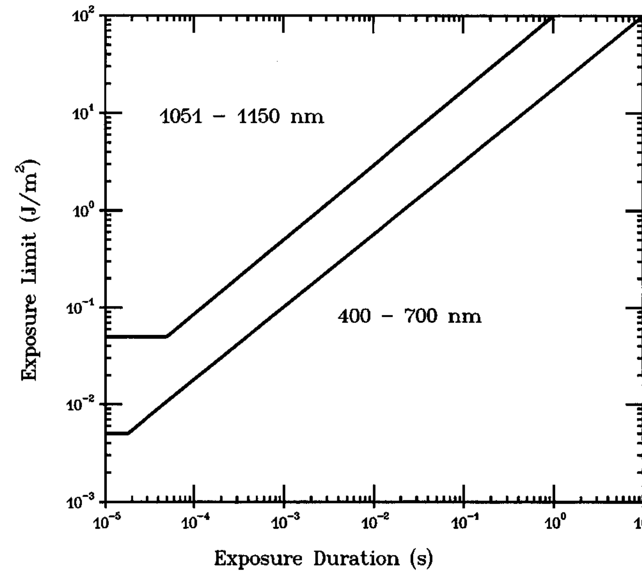

Fig. 5. Exposure limits for intrabeam (direct, point-source) viewing of pulsed laser radiation in the wavelength ranges 400–700 nm and 1,051–1,150 nm (see Table 2).

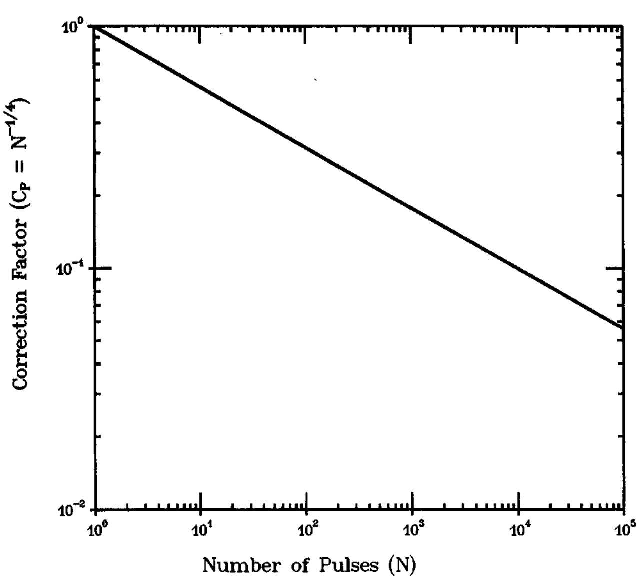

Fig. 4. Repetitive-pulse correction factor C_P is used to determine the exposure limit for a train of N pulses during an exposure of the eye.

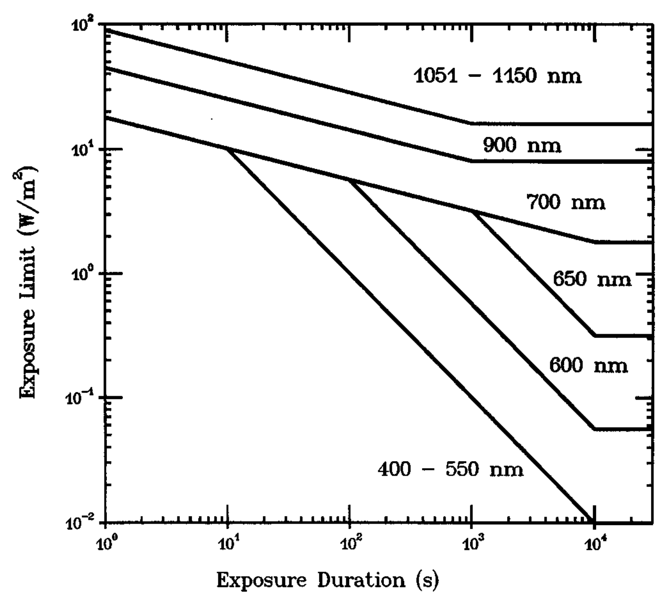

Fig. 6. Exposure limits for intrabeam (direct, point-source) viewing of continuous-wave laser radiation in the wavelength ranges 400–700 nm and 1,051–1,150 nm (see Table 2).

incoherent optical radiation, permits the establishment of guidelines for laser exposure limits. Exposure to direct laser radiation is rare, since the direct beam is normally small and highly collimated, and even modest control measures are effective in limiting access to the direct beam. Emphasis is usually placed on engineering protective measures and use of eye protectors, and the exposure limits are used extensively only as the basis for these protective measures. Further research should expand and strengthen the foundation for these exposure limits. Because of the generally acute nature of laser injury, cumulative exposures to levels approaching the limits should not be regarded as an increased health risk. Since there are thresholds for the laser bioeffects of concern, the known range of individual susceptibility is small and, in view of the safety factors applied to even worst-case exposure conditions, no special limits need be applied to the general population. These guidelines are considered to be adequate for the general population as well as for occupational exposure. No special assumptions such as adult ocular size, pre-exposure of skin, thickness of stratum corneum, or body size were made in deriving the

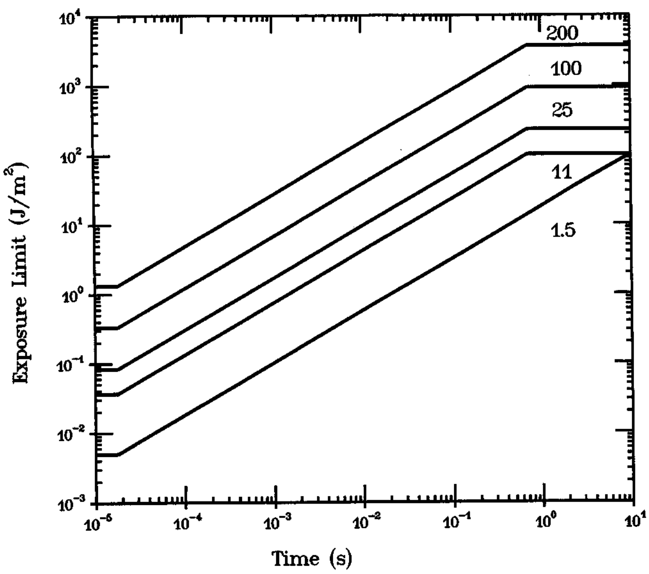

Fig. 7. Exposure limits for direct viewing of an extended source for wavelengths between 400 and 700 nm. Representative values are plotted for several source size angular subtense values from α_{min} (1.5 mrad) to $2\alpha_{max}$ (200 mrad). Numerical values in upper right are in milliradians.

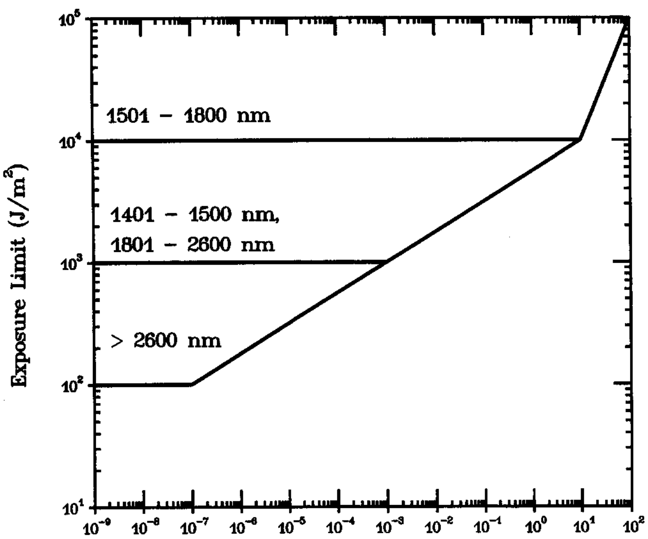

Fig. 8. Exposure limits for ocular exposure to middle and far-infrared laser radiation. For pulsed lasers only and for exposures up to 100 s, penetration depth into tissue results in a variation of exposure limit depending upon wavelength.

limits. Only two exceptions need to be made to the foregoing. Some rare photosensitive or photosensitized individuals may react to UV irradiances below the specified exposure limits, and such people should take more rigorous precautions to avoid exposure to UV radiation. The limits for ocular exposure from 300 to 400 nm do not adequately protect the retina of aphakic individuals or infants, who would require UV absorbing lenses.

The exposure limits presented here should be used as guidelines for controlling human exposure to laser radiation. They should not be regarded as thresholds of injury or as sharp demarcations between "safe" and "dangerous" exposure levels. Exposure at levels below the exposure limits should not result in adverse health effects; the limits incorporate the collective knowledge generated worldwide by scientific research and experience of laser safety, and are based upon the best available published information.

Because of the rapid increase in applications and use of lasers by industry, science, medicine, and the general public, the importance of laser exposure limits will increase. There is a growing need for codes of practice for all potentially hazardous laser operations.

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■■

APPENDIX

USING THE EXPOSURE LIMIT TABLES

Example

To find the intrabeam exposure limit for He-Ne (632.8 nm) for a 0.25-s exposure, use Table 2. First use the left-hand column to find the wavelength. Choose the second 400–700 nm entry since the 0.25-s (aversion response) exposure duration falls between 1.8×10^{-5} and 10 s (second column). The exposure limit (EL) is then

$$\begin{aligned} EL &= 18(t^{3/4})\ J\ m^{-2} = 18(0.25)^{3/4} J\ m^{-2}; \\ &= 6.3\ J\ m^{-2} = 6.3\ W\ s\ m^{-2}; \qquad \text{(A1)} \\ &= (6.3\ W\ s\ m^{-2})/(0.25\ s) = 25\ W\ m^{-2}. \end{aligned}$$