REVISION OF GUIDELINES ON LIMITS OF EXPOSURE TO LASER RADIATION OF WAVELENGTHS BETWEEN 400 nm AND 1.4 μm

International Commission on Non-Ionizing Radiation Protection*

INTRODUCTION

SINCE THE publication of the ICNIRP *Guidelines on Limits of Exposure to Laser Radiation of Wavelengths between 180 nm and 1,000 μm* (1996), recent research has made it appropriate to update the laser retinal protection guidelines for ultrashort (sub-nanosecond) pulse durations and for continuous-wave (CW) exposures lasting 10 s or longer. These revisions are limited to the retinal hazard spectral region (400 nm to 1,400 nm). No changes in the limits are recommended for any exposure duration between 1 nanosecond (ns) and 10 s for intrabeam viewing (nor to 0.7 s for viewing extended sources).

Studies of laser-induced retinal injury from mode-locked laser pulses have been carried out for more than two decades (Goldman et al. 1977); however, until recently threshold data have not appeared to be consistent, nor have the underlying damage mechanisms for sub-nanosecond (sub-ns) laser-induced injury been well understood. The Commission organized a task group† on ophthalmic biophysics to review the scientific data and current knowledge of retinal injury mechanisms to consider recommending an extension of the laser guidelines to pulse durations less than 1 ns. The result of this review is that the Commission believes that for ultrashort laser pulses there is now a reasonably consistent explanation of the non-linear optical phenomena that occur in the eye which cause retinal damage. Thus it is appropriate to recommend limits of exposure for pulse durations between 100 femtoseconds (fs) and 1 ns.

Inconsistencies had been discovered in CW laser exposure limits (ELs) when these limits were applied to intentional viewing of light emitting diodes (LEDs) and diode lasers. Consequently, the Commission also requested the ophthalmic biophysics task group to study the validity of the current guidelines for CW exposures. Prior to the extension of the scope of some laser safety standards to apply to LEDs, general guidance in all laser safety standards was never to view a laser beam directly (intrabeam viewing) and serious efforts to derive accurate ELs for durations exceeding ~10 s did not occur. Indeed, the previous effort had been to simplify the expression, combining both thermal and photochemical damage mechanisms. This approach necessitated very large safety factors to accommodate both injury mechanisms within a single mathematical formulation.

The task group reviewed the past criteria and the effects of eye movements, source size, pupillary response, spectral absorption, and the two competing retinal damage mechanisms (photochemical and thermochemical) upon the potential for retinal injury when viewing a CW laser beam or any small light source. The group recommended splitting the ocular ELs into dual limits: one for photoretinitis (photochemical) and one for retinal burns (thermochemical injury) to eliminate highly inconsistent safety factors. The review showed that the impact of eye movements is greatest for small light sources, but least for large sources. This dual-limit approach follows the same approach used to evaluate incoherent sources.

BACKGROUND

General

There are a number of biophysical and physiological factors that influence the derivation of the ocular ELs for laser exposures. Cell injury from laser pulses of 1 ns to at least 0.25 s is caused by thermo-mechanical damage of cell structures or thermal denaturation of cell proteins. Heat flow from the absorption site plays an important role in the redistribution of incident energy. Thus, whether a cell is located in either the irradiated or an adjacent area will determine its temperature rise and the

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Table 1. Values for t_{min}.

Wavelength range	t_{min}
315–400 nm	1 ns
400–1,050 nm	18 μs
1,050–1,400 nm	50 μs
1.4–1.5 μm	1 ms
1.5–1.8 μm	1 s
1.8–2.6 μm	1 ms
2.6–1,000 μm	100 ns

duration for which that cell is at an elevated temperature (Barnes 1974; Hillenkamp 1989; Mainster et al. 1970; Priebe and Welch 1978; Sliney and Wolbarsht 1980; Sliney 1999). This "time-temperature history" is crucial because of the dependence of thermo-chemical denaturation of proteins on the peak temperature and the entire duration (of many milliseconds or seconds) that the temperature is elevated. Therefore, the geometry of the retinal exposure will influence the retinal lesion size and the threshold in much the same way regardless of the exposure duration of a laser pulse, since most of the thermal denaturation of proteins occurs after the pulse, i.e., during the cooling period (Courant et al. 1989a, 1989b; Sliney and Wolbarsht 1980). Despite the presence of non-linear effects, a similar spot-size dependence also exists in the sub-ns time regime (Goldman et al. 1977; Cain et al. 1996; Rockwell et al. 1997). This permits the use of a single scaling factor (C_E) to adjust the EL from 100 fs to at least 10 s. The correction factor C_E is set as the angular subtense of the source α divided by α_{min} (1.5 milliradian). Histological studies of the sites of small and large retinal image size exposures at 530, 580, and 1064 nm show effects upon the neural retina and in the retinal pigment epithelium. Although the damage in the pigmented epithelium was centered on the melanin granules, it was apparently unrelated to linear absorption by the melanin granules (Toth et al. 1996, 1997; Goldman et al. 1977).

Sub-nanosecond exposures

Guidelines for ELs have not previously existed for sub-ns exposure because of controversies over tissue damage mechanisms; only a very tentative interim guideline to limit peak irradiance to the EL for 1 ns has been recommended (ICNIRP 1996). Studies of laser-induced retinal injury from mode-locked laser pulses in the 10–300 picosecond (ps) time domain and sub-ps exposures in the femtosecond time regime have been carried out in several research programs, and the scientific database is now sufficient for the first time to recommend ELs for pulse durations between 100 fs and 1 ns. The development of ELs in the sub-ns time domain has been very difficult because of different interaction mechanisms of laser radiation with biological tissues (Cain et al. 1997; Roach et al. 1999; Toth et al. 1997). The damage produced by non-linear effects does not follow the same relationship with wavelength, with pulse duration, and with retinal image size as do thresholds from thermal and thermoacoustic damage mechanisms. For this reason, it had been necessary to perform a number of studies of non-linear damage mechanisms (Cain et al. 1997; Gerstman et al. 1996; Hammer et al. 1997; Rockwell et al. 1997). Likewise, the range of potential effects that could occur below the ophthalmoscopically visible threshold had to be studied by histological techniques. The consequences of exceeding the threshold, i.e., supra-threshold effects, also must be understood prior to setting ELs. Fig. 1 shows the ophthalmoscopically determined threshold damage levels from several studies in the sub-ns regime and also shows the new recommended guidelines. A safety factor of approximately 10 to 20 was maintained in the derivation of these limits, the exact magnitude depending upon the level of uncertainty in the measured damage thresholds. Between approximately 10 ps and 1 ns, self-focussing of the ocular media further concentrates laser energy into narrower beams or filaments which increases the retinal radiant exposure and thereby lowers the thresholds (Cain

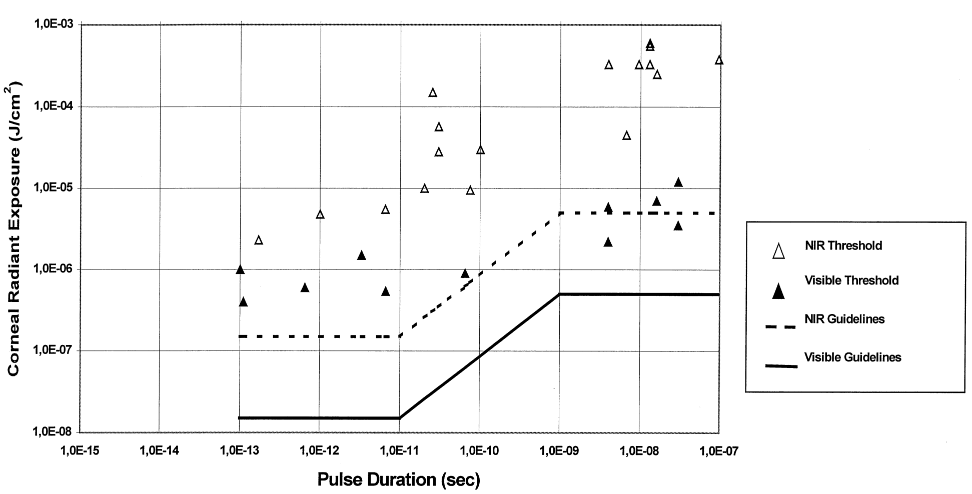

Fig. 1. Laser retinal injury thresholds and 1996 exposure limits for visible and near infrared (NIR) Nd:YAG laser wavelengths, expressed as corneal radiant exposure.

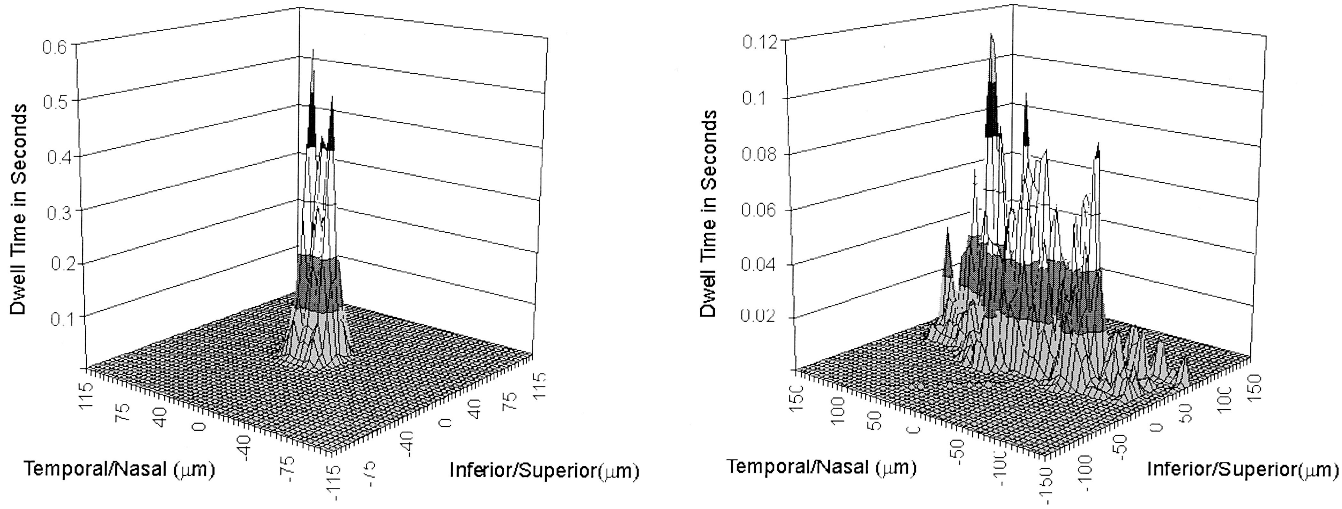

Fig. 2. Distribution of laser energy on the retina produced by eye movements over a 10-s period for a non-human primate under anesthesia (left) and the distribution in the human eye during normal, unrestrained conditions (right) [adapted from Ness et al. (2000)]. The spot size at 50% peak irradiance points increased from a nearly circular 30 μm pattern (left) to an elliptical pattern (right) with an average cross-sectional dimension of 75 μm (right). Energy was also scattered outside the central image.

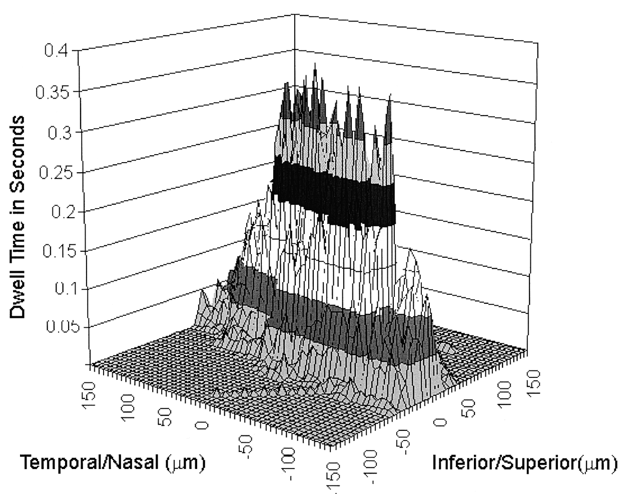

Fig. 3. Distribution of laser energy for 100-s unrestrained viewing [adapted from Ness et al. (2000)]. The minimal spot size was about 135 μm. This leads to a 2.3 reduction in risk from thermal injury. This result is consistent with the 150 to 200 μm elliptical lesions produced when an observer stares at a welding arc (Naidoff and Sliney 1974).

et al. 1997; Roach et al. 1999). The time-dependence of self-focussing is complex and non-linear, but was best fit by a function $f(t^{0.75})$ (Figure 1). Other non-linear optical mechanisms appear to play a role in retinal injury in the sub-ps region (Roach et al. 1999; Rockwell et al. 1997).

CW exposures

Several physiological factors come into play for CW exposures (generally taken as greater than 0.25 s) where the person's visual task will limit the exposure duration and the retinal area illuminated. Physiological factors, such as pupillary activity, eye movements, breathing, heart-beat, blood-flow, other bodily movements, and visual task behavior become important (Andre-Deshays et al. 1988; Eizenman et al. 1980). In addition, at short visible wavelengths, another injury mechanism (photochemical) plays an important role, and synergism between photochemical and thermal injury mechanisms can influence the EL. All of these factors were considered in revising the ELs for exposure durations greater than 10 s.

The ICNIRP task group examined a number of studies of fixational eye movements, and reached a general conclusion regarding image wander over the fovea and macula (Epelboim et al. 1995, 1997; Epelboim 1998; Eizenman et al. 1980; Ferman et al. 1987). Ness and colleagues (1997, 2000) then conducted additional, highly specific, worst-case visual fixation measurements of image wander when a subject was asked to fixate on a very small, fixed target. The subjects were trained, mostly young observers with good vision. Employing the method developed by Ness et al. (1997), the task group attempted to confirm the earlier studies by conservatively simulating the worst-case viewing conditions. The eye-movement studies of Ness et al. (1997, 2000) clearly showed that the retinal image can remain remarkably still for a few seconds, but that within 30 s the central retina (the fovea) must move to other points in space for cognition. Two viewing conditions were studied: with a stabilized head (as could occur with ophthalmic instrument applications of lasers), and without head restraint (normal conditions) while volunteers attempted to fixate on a small "point" light source. The results were evaluated in a variety of ways. The fixation history of the small retinal image diameter d_r (<30 μm) was plotted as a function of time to determine the integration of retinal exposure dose. Figs. 2 and 3 illustrate the accumulated radiant exposure in the retinal image area. This exposure directly predicts the extent and position of photochemical retinal injury, since retinal radiant exposure determines the risk of photoretinitis for a given wavelength. While these data permitted the determination of the photoretinitis ("blue-light hazard") EL value, the determination of the thermal hazard ELs was more complex, since thermal retinal injury thresholds decrease for increasing retinal spot size.

The determination of the potential for retinal thermal injury for long fixation times required an examination of three factors:

1. The time-averaged retinal irradiance;
2. The thermal effects that result from the way eye movements transform a fixed retinal image into the equivalent of a repetitive-pulse exposure; and
3. The manner in which image size affects the retinal thermal injury threshold due to radial heat flow during and after the exposure.

The time-averaged retinal irradiance must not exceed the CW irradiance permitted for a fixed image. The thermal repetitive-pulse exposure obeys what is referred to as the $N^{-0.25}$ additivity rule where the net effect is modified as the number of pulses N raised to the -0.25 power ($N^{-0.25}$). This rule is expressed in the ICNIRP Guidelines (1996) by the correction-factor C_p, which reduces the EL for a single pulse in a train of pulses. However, if multiple pulses exist with a duration t_{min} (Table 1), those pulses are treated as if they were a single pulse.

These interrelated factors were dealt with by trial and error and by examining a few worst-case conditions. If the retinal image moved very little during the entire viewing time, the average irradiance condition dominated. However, for viewing with an unrestrained head, the retinal image moves dramatically, and the same retinal area may be exposed a number of times during the entire viewing sequence at a low "duty cycle," and the $N^{-0.25}$ additivity function dominates. The instantaneous image size was also considered in these calculations, which modified the results.

Correction factors for eye movements, as it turned out, were only important for viewing durations exceeding 10 s. Only the thermal mechanism is important at durations less than 1 s for small images. Although the physiological eye movements known as saccades do spread the absorbed energy in minimal retinal images (of the order of 25 μm or less) within the 0.1 to 10 s time regime, the limits recommended in these guidelines provide an added safety factor for this viewing condition. At 0.25 s with unrestrained head viewing, the mean retinal spot illuminated is spread out to approximately 50 μm. By 10 s, the illuminated retinal zone becomes approximately 75 μm and the added safety factor for the minimal image condition becomes 1.7 over a stabilized eye, with the spot-size dependence taken into account. By 100 s, it is rare to achieve an illuminated zone (measured at 50% points) as small as 135 μm and this means that there is, in effect, an additional safety factor of 2.3 or more above the minimal image condition. The data from eye-movement studies and retinal thermal injury studies were combined to derive a break-point in viewing time T_2 at which eye movements compensated for the increased theoretical risk of thermal injury for increased retinal exposure durations if the eye were immobilized. Because the thermal injury threshold, expressed as radiant power entering the eye, decreases as the exposure duration t raised to the -0.25-power (i.e., a reduction of only 44% per tenfold increase in exposure duration), moderate increases in the exposed retinal area will compensate for the increased risk for longer viewing times. The increase in retinal area of irradiation resulting from greater eye movements with increased viewing time (Velichovsky et al. 1996) takes longer to compensate for the reduced impact of thermal diffusion with larger extended sources. Thus for increasing angular subtense α the break-point T_2 increases from 10 s for small sources to 100 s for larger sources. Beyond 100 s there is no further increase in risk of thermal injury for small and intermediate size images. The specification of limits and measuring conditions specified here attempt to follow these variables with some simplification leading to a conservative determination of risk.

A pupil size of 7 mm is unrealistically large for lengthy viewing durations, leading to a still greater safety factor for all image sizes. It is conservatively assumed that retinal thermal injury thresholds vary inversely with retinal image size (stabilized) between approximately 25 μm and 1 mm (corresponding to angles of 1.5 to 59 mrad). There is a transition range from 1 mm to approximately 1.7 mm, and beyond 1.7 mm (i.e., visual angles greater than 100 mrad) there is virtually no spot-size dependence when limits are expressed at the retina. When expressed at the cornea, the ELs become a constant radiance for angles greater than 100 mrad.

For photochemically induced retinal injury there is no spot size dependence for a stabilized image. Unlike thermal injury mechanism, the thresholds for photochemical injury are highly dependent upon wavelength and are exposure dose (radiant exposure) dependent; i.e., the thresholds expressed as irradiance decrease inversely with the lengthening of exposure time. Photochemical retinal injury from welding arcs subtending angles of around 1–1.5 mrad show typical lesion sizes of the order of 185–200 μm (corresponding to visual angles of 11–12 mrad), clearly demonstrating the influence of eye movements during fixation. This and other studies of eye-movements during fixation underpinned the derivation of ELs to protect against photochemical retinal injury. These studies also led to the ELs to be specified as an irradiance or radiance defined for a cone angle of acceptance (field-of-view, or FOV) of 11 mrad for an exposure duration between 10 and 100 s. Hence, sources with an angular subtense α less than 11 mrad were treated as equivalent to small, "point-type" sources. This approach was not strictly correct when expressing an EL as an irradiance measurement of an 11-mrad source is not equivalent to irradiance averaging over a field-of-view (γ) of 11 mrad, unless the source had a rectangular ("top-hat") radiance distribution. Thus, in this revision of the guidelines, a distinction is made between angular subtense of a source and radiance (or irradiance) averaging for photochemical EL values. For viewing times in excess of approximately 30–60 s, the influence of saccadic eye motion during fixation is generally overtaken by behavioral movements determined by visual task, and it is quite unreasonable to assume that a light source would be imaged solely in the fovea for a duration longer than 100 s. For this reason, the averaging angle γ is increased linearly with the square-root of t. The minimal angular subtense α_{min} correctly remains at the reference angle of 1.5 mrad for all exposure durations used in thermal retinal hazard evaluation. However, for photochemical retinal hazard assessment, the concept is actually different, as the angle γ is a linear angle defining the cone angle of acceptance for averaging irradiance, and it is important to note that this applies only for extended sources greater than approximately 11 mrad.

The impact of eye movements is dramatic for minimal retinal spot sizes and permits a leveling of the thermal EL for $\alpha < 1.5$ mrad to a constant irradiance of 1 mW cm^{-2} in the visible spectrum (400–700 nm) for $t >$ 10 s. However, as would be expected, there is only a small impact for a source size of 100 mrad, and the plateau of no further risk of retinal injury due to eye movements does not occur until 100 s. For photochemical injury, eye movements had already been incorporated into the visible laser limits for an exposure duration between 10 and 100 s. Beyond 100 s, it is probably unreasonable to assume that fixation could realistically take place, and it was concluded that the limits for all but very large sources (greater than 100 mrad) should end there. This same rationale was followed by the Commission in the derivation of the guidelines for incoherent sources (ICNIRP 1997).

No changes in the measurement apertures (which average irradiance and radiant exposure) are recommended. The use of a 7-mm pupillary aperture was retained in the derivation of the thermal guidelines for all wavelengths, even for visible wavelengths, since the thermal damage mechanisms dominate in the near-infrared and red end of the visible spectrum, where the pupillary response is weakest or non-existent. However, for short wavelengths in the visible, a 3-mm aperture was used (as previously) for the derivation of the photochemical limits, since pupillary constriction will be present at these wavelengths. However, because of physiological movements over several seconds of fixation, the 7-mm aperture averaging is still appropriate. In other words, although a 3-mm pupil was assumed in the derivation of the photochemical limits, to assess exposures of the eye one is to use a 7-mm pupil. This same approach was followed previously in the derivation of visible ELs for the different wavelengths.

Table 2. Exposure guidelines.

Wavelength range	Pulse duration t	Exposure guideline EL
400 to 1,050 nm	10^{-13} to 10^{-11} s (100 fs to 10 ps)	$1.5\ C_A \times 10^{-4}$ J/m^2 ($1.5\ C_A \times 10^{-8}$ J/cm^2)
400 to 1,050 nm	10^{-11} to 10^{-9} s (10 ps to 1 ns)	$2.7\ C_A\ t^{0.75} \times 10^4$ J/m^2 ($2.7\ C_A t^{0.75}$ J/cm^2)
1,050 to 1,400 nm	10^{-13} to 10^{-11} s (100 fs to 10 ps)	$15\ C_C \times 10^{-4}$ J/m^2 ($15\ C_C \times 10^{-8}$ J/cm^2)
1,050 to 1,400 nm	10^{-11} to 10^{-9} s (10 ps to 1 ns)	$27\ C_C\ t^{0.75} \times 10^4$ J/m^2 ($27\ C_C t^{0.75}$ J/cm^2)
Other wavelengths	10^{-13} to 10^{-9} s (100 fs to 1 ns)	Maintain irradiance limit of the 1996 1-ns EL[a]

[a] This is the current, 1996 interim guideline. Research to establish ELs in these spectral regions is planned, as very few data exist (Wantabe et al. 1991) for the skin or cornea.

PROPOSALS FOR REVISED ELS

Sub-ns exposure ELs

For sub-ns exposures, the Commission recommends the guidelines for single-pulse exposures at pulse durations between 100 fs (10^{-13} s) and 1 ns (10^{-9} s) be reduced to the values in Table 2.

Research is also underway in the temporal region of 10 to 100 fs in the visible and IR-A bands. (Note: The spectral correction factors C_A and C_C account for reduced retinal exposure in the IR-A band and are defined in Table 3.)

CW exposure ELs

Since the risk of retinal injury from viewing a CW light or near-infrared source depends upon three variables—time, wavelength and angular subtense (Lund et al. 1998; Sliney 1996; Zuclich et al. 1998)—and the angular dependence is not constant for all wavelengths and exposure durations, the Commission concluded that a single EL function for some wavelengths was not possible. The Commission concluded that ELs for times greater than 1 s required a dual limit approach for short-wavelength light as followed for the incoherent optical radiation ELs. The ELs are therefore expressed as the lowest of two values:

1. For the CW thermal EL, the Commission recommends a limit of $18\ C_A C_E t^{0.75}$ J m^{-2} ($1.8\ C_A C_E t^{0.75}$ mJ cm^{-2}) as now used for $\lambda > 700$ nm (where $C_A = 1.0$ from 400 nm to 700 nm); and this would apply to all wavelengths in the retinal hazard region (i.e., from 400 to 1,400 nm) up to a duration that will now be termed T_2 where the movement of the image over the retina dominates and limits the possibility of a thermal injury, rather than $t = 1{,}000$ s, where near-infrared limits currently become constant irradiance values; and
2. For the CW photochemical ("blue-light" or photoretinitis) EL, the Commission recommends a limit of 100 C_B J m^{-2} defined for a measurement cone-angle-of-acceptance (FOV, γ) of 11 mrad for $t \leq 100$ s. For $t >$ 100 s, an increasing FOV $\gamma = 1.1\sqrt{t}$ is applied. These limits lead to the result that for any small source subtending an angle less than 11 mrad, this

Table 3. Proposed changes to CW laser guideline exposure limits.

Wavelength range (nm)	Exposure duration	Exposure limit (EL)[a]	Comments
400–1,400 nm	1 ns $< t <$ 1 s	*No Change* in limit values, except to eliminate the increased value of α_{min} for $t > 0.7$ s.[b]	Original limits well established as thermal damage mechanism. However, eye movement research required a change.[b]
400–600 nm	1 s $< t <$ 100 s	H = 10 C_B mJ/cm^2 where FOV γ = 11 mrad, (i.e., $\Omega = 10^{-4}$ sr), and equivalent to: L = 100 C_B J/(cm^2 sr) where FOV γ = 11 mrad.	Photochemical: Assumes FOV γ = 11 mrad which is over-conservative for $t > 100$ s; therefore, a new proposal for meas. FOV $\gamma = 1.1 \sqrt{t}$ mrad for $t > 100$ s ($\Omega = t$ μsr)
	100 s $< t < 10^4$ s	E = 0.1 C_B mW/cm^2 (i.e., L = 100 C_B J/(cm^2 sr) for meas. FOV $\gamma = 1.1 \sqrt{t}$ (mrad, important when $\alpha > 11$ mrad).	First dual limit to protect against photochemical injury (i.e., photoretinitis).
400–600 nm	1 s $< t < T_2$ s	H = 1.8 $t^{0.75}$ C_E mJ/cm^2	Based only upon thermal effects.
	T_2 s $< t <$ 30 ks	E = 1.8 C_E $T_2^{-0.25}$ mW/cm^2 for $\alpha > 1.5$ mrad	Second dual limit to protect against retinal thermal injury.
600–1,400 nm	1 s $< t < T_2$	H = 1.8 C_A C_E C_C $t^{0.75}$ mJ/cm^2	Original limits over-stated large-image thermal damage mechanisms, and eye movements not adequately addressed for CW exposures.
		E = 1.0 C_A C_C mW/cm^2 for $\alpha < 1.5$ mrad	
	$T_2 < t <$ 30 ks	E = 1.8 C_A C_C C_E $T_2^{-0.25}$ mW/cm^2 for $\alpha > 1.5$ mrad	

[a] C_B = 1.0 for $\lambda < 450$ nm (referred to as the new C_3 in IEC terminology); $C_B = 10^{0.02(\lambda-450)}$ for $\lambda > 450$ nm; and $T_2 = 10[10^{(\alpha-1.5)/98.5}]$ limited to T_2 = 10 s for $\alpha < 1.5$ mrad and 100 s if $\alpha > 100$ mrad; C_A = 1.0 for $\lambda < 700$ nm; $C_A = 10^{0.002(\lambda-700)}$ for 700 nm $< \lambda <$ 1,050 nm; C_A = 5.0 for 1,050 $< \lambda <$ 1,400 nm; and C_C = 1.0 for $\lambda <$ 1,150 nm; $C_C = 10^{0.018(\lambda-1,150)}$ for 1,150 $< \lambda <$ 1,200 nm; C_C = 8.0 for 1,200 nm $< \lambda <$ 1,400 nm; $C_E = \alpha/\alpha_{min}$ where λ is expressed in nm and α is expressed in milliradians (mrad).
[b] α_{min} now is 1.5 mrad for all thermal retinal hazard ELs.

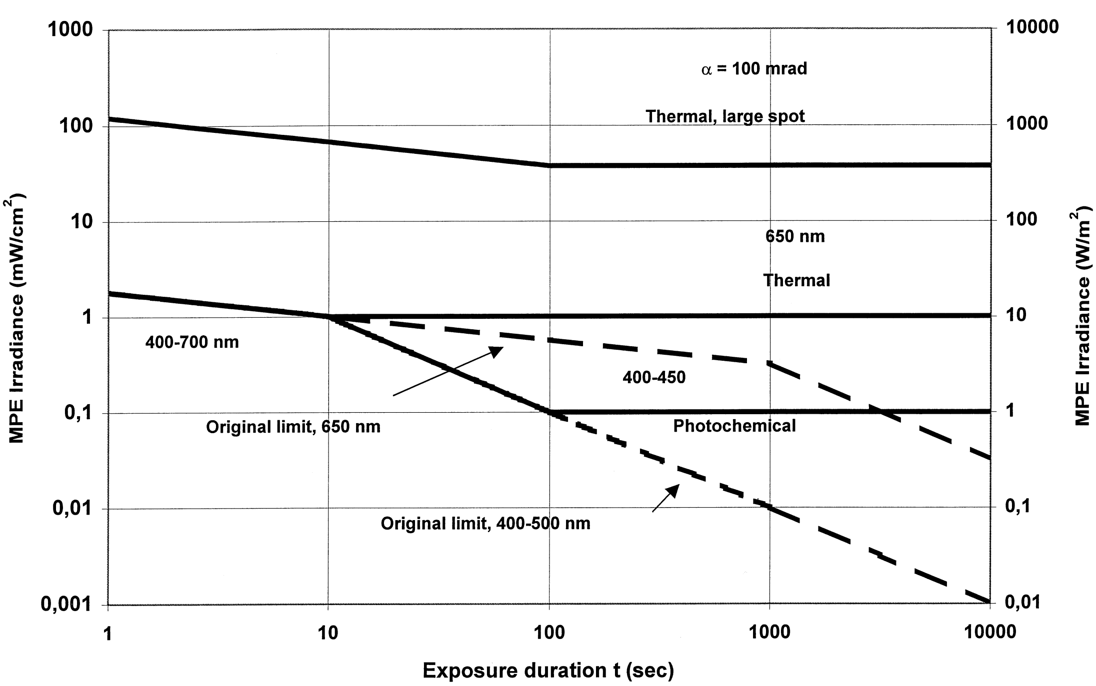

Fig. 4. The guideline EL for a minimal-image, 400 nm to 450 nm blue-laser exposure is a single value, independent of source-size, averaged over an 11 mrad field-of-view for 10–100 s exposures—whereas the guideline for 650-nm red laser exposures varies with source size. Note that source size directly plays a role only in the retinal thermal ELs. For photochemical limits for $t > 100$ s, the measurement cone angle γ increases with time.

Table 4. Laser exposure limits for the eye.

Wavelength λ (nm)	Exposure duration t (s)	Exposure limit EL (J/cm² or W/cm²)	Exposure limit EL (J/m² or W/m²)	Restrictions
Ultraviolet				
Dual limits for 180–600 nm ultraviolet laser exposures at t > 1 ns:				
Photochemical				
180 to 302	1 ns to 30 ks	3 mJ/cm²	30 J/m²	Aperture sizes:
303	1 ns to 30 ks	4 mJ/cm²	40 J/m²	1 mm for $t < 0.3$ s
304	1 ns to 30 ks	6 mJ/cm²	60 J/m²	1.5 $t^{0.375}$ mm for
305	1 ns to 30 ks	10 mJ/cm²	100 J/m²	0.3 s $< t <$ 10 s
306	1 ns to 30 ks	16 mJ/cm²	160 J/m²	3.5 mm for $t >$ 10 s
307	1 ns to 30 ks	25 mJ/cm²	250 J/m²	
308	1 ns to 30 ks	40 mJ/cm²	400 J/m²	
309	1 ns to 30 ks	63 mJ/cm²	630 J/m²	
310	1 ns to 30 ks	0.1 J/cm²	1.0 kJ/m²	
311	1 ns to 30 ks	0.16 J/cm²	1.6 kJ/m²	
312	1 ns to 30 ks	0.25 J/cm²	2.5 kJ/m	
313	1 ns to 30 ks	0.40 J/cm²	4 kJ/m²	
314	1 ns to 30 ks	0.63 J/cm²	6.3 kJ/m²	
315 to 400	10 s to 30 ks	1.0 J/cm²	10 kJ/m²	
Thermal				
180 to 400	1 ns to 10 s	$0.56t^{0.25}$ J/cm²	$5.6t^{0.25}$ kJ/m²	
Visible				
400 to 700	100 fs to 10 ps	0.015 C_E μJ/cm²	0.15 C_E mJ/m²	
400 to 700	10 ps to 1 ns	2.7 C_E $t^{0.75}$ J/cm²	27 C_E $t^{0.75}$ kJ/m²	
400 to 700	1 ns to 18 μs	0.5 C_E μJ/cm²	5 C_E mJ/m²	
400 to 700	18 μs to 10 s	$1.8C_E$ $t^{0.75}$ mJ/cm²	$18C_E$ $t^{0.75}$ J/m²	
Dual limits for 400–600 nm visible laser exposures at t > 10 s				(all for 7-mm limiting aperture)
Photochemical[a]				
400 to 600	10 s to 100 s	10 C_B mJ/cm²	100 C_B J/m²	for $\alpha <$ 11 mrad (γ = 11 mrad[a])
400 to 600	100 s to 30 ks	0.1 C_B mW/cm²	1 C_B W/m²	for $\alpha <$ 11 mrad
400 to 600	100 s to 10 ks	0.1 C_B mW/cm²	1 C_B W/m²	for $\alpha >$ 11 mrad (γ = 1.1 $t^{0.5}$ mrad)
400 to 600	10 ks to 30 ks	10 C_B mW/(cm² sr)	100 C_B W/(m² sr)	(See Note[a])
Thermal[a]				(all for 7-mm limiting aperture)
400 to 700	10 s to 30 ks	1.0 mW/cm²	10 W/m²	for $\alpha <$ 1.5 mrad
400 to 700	10 s to T_2 s	1.8 C_E $t^{0.75}$ mJ/cm²	18 C_E $t^{0.75}$ J/m²	for $\alpha >$ 1.5 mrad
400 to 700	T_2 s to 30 ks	1.8 C_E $T_2^{-0.25}$ mW/cm²	18 C_E $T_2^{-0.25}$ W/m²	for $\alpha >$ 1.5 mrad
Near Infrared, IR-A				
700 to 1,050	100 fs to 10 ps	0.015 C_A C_E μJ/cm²	0.15 C_A C_E mJ/m²	7 mm limiting aperture
700 to 1,050	10 ps to 1 ns	2.7 C_A C_E $t^{0.75}$ μJ/cm²	27 C_A C_E $t^{0.75}$ mJ/m²	
700 to 1,050	1 ns to 18 μs	0.5 C_A C_E μJ/cm²	5 C_A C_E mJ/m²	
700 to 1,050	18 μs to 10 s	1.8 C_A C_E $t^{0.75}$ mJ/cm²	18 C_A C_E $t^{0.75}$ J/m²	
1,051 to 1,400	100 fs to 10 ps	0.15 C_C C_E μJ/cm²	1.5 C_C C_E mJ/m²	
1,051 to 1,400	10 ps to 1 ns	27 C_C C_E $t^{0.75}$ J/cm²	270 C_C C_E $t^{0.75}$ kJ/m²	
1,051 to 1,400	1 ns to 50 μs	5 C_C C_E μJ/cm²	50 C_C C_E mJ/m²	
1,051 to 1,400	50 μs to 10 s	9.0 C_C C_E $t^{0.75}$ mJ/cm²	90 C_C C_E $t^{0.75}$ J/m²	
700 to 1,400	10 s to 30 ks	1.0 C_A C_C mW/cm²	10 C_A C_C W/m²	for $\alpha <$ 1.5 mrad
700 to 1,400	10 s to T_2 s	1.8 C_A C_C C_E $t^{0.75}$ mJ/cm²	18 C_A C_C C_E $t^{0.75}$ J/m²	for $\alpha >$ 1.5 mrad
700 to 1,400	T_2 s to 30 ks	1.8 C_A C_C C_E $T_2^{-0.25}$ mW/cm²	18 C_A C_C C_E $T_2^{-0.25}$ W/m² NTE[b] 100 mW/cm²	for $\alpha >$ 1.5 mrad
Far Infrared				
1,400 to 1,500 nm	1 ns to 1 ms	0.1 J/cm²	1 kJ/m²	Aperture sizes:
1,400 to 1,500 nm	1 ms to 10 s	$0.56t^{0.25}$ J/cm²	$5.6t^{0.25}$ kJ/m²	1 mm for $t < 0.3$ s
1,500 to 1,800 nm	1 ns to 10 s	1.0 J/cm²	10 kJ/m²	1.5 $t^{0.375}$ mm for
1,801 to 2,600 nm	1 ns to 1 ms	0.1 J/cm²	1 kJ/m²	0.3 s $< t <$10 s
1,801 to 2,600 nm	1 ms to 10 s	$0.56t^{0.25}$ J/cm²	$5.6t^{0.25}$ kJ/m²	
2,601 nm to 1 mm	1 ns to 100 ns	10 mJ/cm²	100 J/m²	3.5 mm for $t >$ 10 s
2,601 nm to 1 mm	100 ns to 10 s	$0.56t^{0.25}$ J/cm²	$56t^{0.25}$ kJ/m²	
1,400 nm to 1 mm	10 s to 30 ks	100 mW/cm²	1 kW/m²	

[a] For small sources subtending an angle of 1.5 mrad or less, the visible dual limit ELs from 400 nm to 600 nm, for times greater than 10 s, reduce to the thermal limits for times less than T_1 and to photochemical limits for longer times. T_1 = 10 s for λ < 450 nm; $T_1 = 10 \times 10^{0.02(\lambda-450)}$ for 450 nm < λ < 500 nm; and T_1 = 100 s for λ > 500 nm. The photochemical retinal hazard limit may also be expressed as an integrated radiance L = 100 C_B J/(cm² sr); T_2 see Table 5.

[b] NTE = Not to exceed; see Table 5 for definitions of constants.

Table 5. Laser exposure limits for the skin.[ab]

Wavelength λ (nm)	Exposure duration t (s)	Exposure limit EL (J/cm^2 or W/cm^2)	Exposure limit EL (J/m^2 or W/m^2)	Restrictions
Ultraviolet				
180 to 400	1 ns to 30 ks	Same as Eye EL		
Visible and IR-A				
400 nm to 1,400 nm	1 ns to 100 ns	20 C_A mJ/cm^2	200 C_A J/m^2	3.5 mm limiting aperture
400 nm to 1,400 nm	100 ns to 10 s	1.1 C_A $t^{0.25}$ J/cm^2	11 C_A $t^{0.25}$ kJ/m^2	
400 nm to 1,400 nm	10 s to 30 ks	0.2 C_A W/cm^2	2 C_A kW/m^2	
Far infrared				
1,400 nm to 1 mm	1 ns to 30 ks	Same as Eye EL for 1,400 nm to 1 mm		3.5 mm limiting aperture

[a] Notes for all EL tables: Angles: All values of α and γ in milliradians (mrad). Wavelength: All values of wavelength (2) in nanometers (nm). Time: All values of t in s; 1 ks = 1,000 s, and 30 ks = 8 h.

1. Spectral Correction Factors: $C_A = 1$ for $\lambda = 400$ to 700 nm; $C_A = 10^{[0.002(\lambda-700)]}$ if $\lambda = 700 - 1{,}050$ nm; $C_A = 5.0$ if $\lambda = 1{,}051$–1,400 nm; $C_B = 1$ for 400 nm $< \lambda \leq 450$ nm; $C_B = 10^{0.02(\lambda-450)}$ if $\lambda = 400$–700 nm; $T_2 = 10[10^{(\alpha-1.5)/98.5}]$ s; for 1.5 mrad $< \alpha <$ 100 mrad; $T_2 = 10$ s for $\alpha <$ 1.5 mrad and $T_2 = 100$ s if $\alpha >$ 100 mrad; $C_C = 1$ for $\lambda \leq 1{,}150$; $C_C = 10^{0.0181(\lambda-1{,}150)}$ for $1{,}150 < \lambda < 1{,}200$; $C_C = 8$ for $1{,}200 \leq \lambda < 1{,}400$.

2. Angular subtense α of a source and limiting cone angle measuring field-of-view γ: α_{min} is 1.5 mrad for all thermal retinal hazard exposure limits. $\gamma = 11$ mrad for $t \leq 100$ s, $\gamma = 1.1\ t^{0.5}$ mrad for 100 s $< t <$ 10,000 s, and $\gamma = 110$ mrad for $t > 10^4$ s. $T_2 = 10[10^{(\alpha-1.5)/98.5}]$ such that $T_2 = 10$ s for $\alpha <$ 1.5 mrad and 100 s if $\alpha >$ 100 mrad.

3. Extended Source ELs: For extended-source viewing of laser radiation (e.g., diffuse reflection) between 400 nm and 1,400 nm, the thermal ELs include the correction factor C_E provided that the angular subtense of the source (measured at the viewer's eye) is greater than α_{min}, where α_{min} is:

$$\alpha_{min} = 1.5 \text{ mrad for all thermal limits}$$

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

$$C_E = \alpha/\alpha_{min} \text{ for } \alpha_{min} < \alpha < 100 \text{ mrad.}$$

$$C_E = \alpha^2/(\alpha_{min} \times \alpha_{max}) \text{ for } \alpha > 100 \text{ mrad where } \alpha_{max} = 100 \text{ mrad.}$$

The angle of 100 mrad may also be referred to as α_{max} at which point the extended source limits can be expressed as a constant radiance using the last equation written in terms of α_{max}:

$$L_{EL} = (8.5 \times 10^3)(EL_{\text{pt source}})\text{J/(cm}^2\text{ sr)} \quad \text{for} \quad t < 10 \text{ s.}$$

$$L_{EL} = 100C_B\text{J/(cm}^2\text{sr)} \quad \text{for} \quad t > 1\text{s}$$

[b] For retinal photochemical limits, where the radiance is measured over a cone angle of acceptance (field-of-view) γ which increases from 11 mrad for times less than 100 s to 110 mrad for times greater than 10 ks.

4. Terminology: The term Exposure Limit (EL) is used by ICNIRP. The same values are termed MPEs (Maximum Permissible Exposure Limits) by ANSI and IEC, and termed TLVs (Threshold Limit Values) by ACGIH. Essentially all groups have the same limit values.

radiance limit corresponds to a corneal irradiance of 1.0 C_B W m^{-2} (0.1 C_B mW cm^{-2}) for $t >$ 100 s. This photoretinitis limit is only required for wavelengths between 400 nm and 600 nm. From a photobiological standpoint, the action spectrum used for incoherent sources, B(λ) should be used (Ham and Mueller 1989); however, for simplicity, it was concluded that C_B should have a value of 1.0 between 400 and 450 nm, and then a power function between 450 nm and 600 nm: $C_B = 10^{0.02(\lambda-450)}$ (where λ is expressed in nm). The ELs are therefore similar to, but are slightly more conservative than, the incoherent limits to account for the uncertainties in the photoretinitis action spectrum which are more critical for monochromatic radiation. The break point where intra-beam (minimal-image) photochemical limits apply rather than 10 W m^{-2} (1.0 mW cm^{-2}) is again termed T_1 as in previous guidelines, since it is the transition from dominantly thermal to dominantly photochemical injury.

Fig. 4 shows how the guideline values appear for two representative wavelengths: where photochemical mechanisms dominate (450 nm) and where thermal mechanisms dominate (650 nm).

Repetitive exposures

Each of the following three general rules should be applied to all repetitive exposures as occur from repetitively pulsed or scanning laser systems:

1. The exposure from any single pulse in a train of pulses shall not exceed the EL for a single pulse of that pulse duration;
2. The exposure from any group of pulses (or sub-group of pulses in a train) delivered in time T shall not exceed the EL for time T; and
3. The exposure from any single pulse within a group of pulses shall not exceed the single-pulse EL multiplied by a cumulative-thermal correction factor $C_P = N^{-0.25}$,

where N is then number of pulses. This rule applies only to ELs to protect against thermal injury, where all pulses delivered in less than t_{min} are treated as a single pulse (Table 1). The inflection point, t_{min} is 1 ns for wavelengths between 315 and 400 nm, is 18 μs for wavelengths between 400 and 1,050 nm, is 50 μs for wavelengths between 1,050 and 1,400 nm, is 1 ms for wavelengths between 1.4 and 1.5 μm and between 1.8 and 2.6 μm, is 1 s between 1.5 and 1.8 μm, and is 100 ns for wavelengths between 2.6 and 1,000 μm.

RESTRICTIONS

The guidelines apply to normal, awake, task-oriented viewing conditions and normally cannot be applied directly to ocular exposure from ophthalmic instruments or head-mounted ocular illuminators, where the impact of normal head movements is neutralized. Tables 4 and 5 provide the final updated summary of all laser ELs for eye and skin.

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