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GUIDELINES ON LIMITS OF EXPOSURE TO INCOHERENT VISIBLE AND INFRARED RADIATION (0.38 to 3 µm)

International Commission on Non-Ionizing Radiation Protection*

1. INTRODUCTION

Guidelines for exposure to visible and infrared radiation were first proposed by ICNIRP in 1997 (ICNIRP 1997). Related guidelines on limits of exposure to UVR (ICNIRP 2004) and laser radiation have been published (ICNIRP 1996) and revised (ICNIRP 2000).

Since the publication of the ICNIRP Guidelines on Limits of Exposure to Broad-Band Incoherent Optical Radiation (0.38 to 3 µm) in 1997 (ICNIRP 1997), further research on thermally induced injury of the retina (Schulmeister; Stuck; Lund; Sliney 2011) has led to the need to revise the guidance given so far. In particular, the exposure limit dependence upon source size is now a function of the exposure duration. Further, the retinal thermal hazard function has been revised. The specific rationale for these changes is provided in the Annex (12 Rationale for the changes since the previous guidelines).

2. PURPOSE AND SCOPE

The purpose of these guidelines is to establish the basic principles of protection of the eyes and the skin against the hazards of incoherent visible and infrared radiation emitted all sources of optical radiation, with the exception of lasers, (see section 3 on wavelength band definitions). Separate guidelines are defined for exposure to laser radiation (ICNIRP 1996, ICNIRP 2000). The guidelines are intended for use by the various 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 optical radiation.

The exposure limits given are for exposure durations between 1 µs and 8 hours and apply to radiation at wavelengths from 380 nm to 3 000 nm (3 µm). However, the action spectrum for photochemically induced photoretinopathy extends to 300 nm in the ultraviolet (UVR) wavelength range and should be applied for the evaluation of broad-band sources which may also emit UVR. Separate guidelines apply for the exposure of the skin and the anterior parts of the eye to UVR (ICNIRP 2004).

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Injury thresholds are well defined for the effects that are in the scope of these guidelines. Therefore, in contrast to the ICNIRP guidelines for electromagnetic fields with wavelengths greater than 1 mm, the guidelines for optical radiation in general do not differentiate between exposure to professionals and exposure to the general public. The only exemption concerns the action spectrum for photochemically induced photoretinopathy, where for children below 2 years of age the aphakic hazard function should be applied.

Exposure limits for incoherent infrared radiation of wavelength between 3 µm and 1 mm are not provided because non-laser sources do not emit enough power in this region to cause a health hazard other than the possibility of heat stress (ICNIRP 2006).

The guidelines apply to exposures to optical radiation producing acute onset of observable biological responses since there is a lack of knowledge regarding the health risks for long term chronic exposure. However, current knowledge imply that there are no effects of chronic exposure to infrared radiation, below the exposure limit here provided.

These guidelines do not apply to deliberate exposure for medical (diagnostic or treatment) purposes.

Detailed measurement procedures and calculation methods are beyond the scope of this document and are provided elsewhere (Sliney; Wolbarsht 1980, UNEP; WHO; IRPA; WHO 1982, McCluney 1984, CIE; ICNIRP 1998, Schulmeister 2001, Henderson; Schulmeister 2004)

3. QUANTITIES, SYMBOLS AND UNITS

Electromagnetic radiation in the wavelength range between 100 nm and 1 mm is widely termed "optical radiation". A subdivision of this spectral band is defined by the International Commission on Illumination (CIE 2009) and can be useful in discussions of the photobiological effects of optical radiation, although the predominant effects have less sharply defined spectral limits. According to the CIE the subdivision of optical radiation of wavelengths 100– 400 nm is termed ultraviolet radiation (UVR). CIE specifies the visibility function $v(\lambda)$ for visual perception of radiation (or 'light') in the wavelength range of 380 – 780 nm. Radiation in the wavelength range 780 nm to 1 mm is known as infrared radiation (IRR). The infrared region is often subdivided into IR-A (780 – 1 400 nm), IR-B (1 400 – 3 000 nm), and IR-C (3 000 nm – 1 mm).

Exposure limits for optical radiation are expressed in different radiometric quantities, depending on the tissue and damage mechanism (Table 1).

Table 1 Quantities symbols and units

Quantity	Symbol	Unit
Power	Φ	W
Energy	Q	J
Irradiance	E	$W\ m^{-2}$
Radiant exposure	H	$J\ m^{-2}$
Radiance	L	$W\ m^{-2}\ sr^{-1}$
Radiance dose/Time-integrated radiance	D	$J\ m^{-2}\ sr^{-1}$

Exposure limits that relate to the skin, the anterior part of the eye or to potential retinal photochemical injury under the “small source” condition are expressed in the radiometric quantities of *irradiance, E* ($W\ m^{-2}$) and *radiant exposure*, *H* ($J\ m^{-2}$). The quantity of radiant exposure is also sometimes referred to as dose, and irradiance can be understood as dose-rate. *Radiance, L* ($W\ m^{-2}\ sr^{-1}$), and *radiance dose* (D , $J\ m^{-2}\ sr^{-1}$), also referred to as time-integrated radiance, are used for exposure limits that relate to retinal injury from extended sources, i.e. sources that give rise to an image on the retina. Radiance is convenient since it is directly related to the irradiance at the retina (Sliney; Wolbarsht 1980, Henderson; Schulmeister 2004).

Depending on the type of interaction, the effectiveness to produce an adverse effect can be strongly wavelength dependent. This wavelength dependence is accounted for by an action spectrum that is used to spectrally weigh the respective exposure quantities. These exposure quantities (that are compared to the respective exposure limits) are then referred to as, for instance, “effective” irradiance.

4. SOURCES AND EXPOSURE CONDITIONS

Optical radiation from artificial sources is used in a wide variety of industrial, consumer, scientific, and medical applications, and in most instances the light and infrared energy emitted is not hazardous to the general public. However, people with certain medical conditions may be at risk from exposures that are otherwise innocuous. In certain unusual exposure conditions potentially hazardous levels are accessible. Examples include; arc welding, use of some arc lamps in research laboratories, very high intensity flash lamps in photography, infrared lamps for surveillance and heating, a number of medical diagnostic applications, and even printing and photocopying. Excessive light and infrared radiation are typically filtered or baffled to reduce discomfort. Where sufficient visible light is present, the natural aversion response of the eye to bright light will substantially reduce potentially hazardous exposure. Moreover, if the total irradiance is sufficiently high, the thermal discomfort, sensed by the skin and cornea may produce an aversion response and tend to limit exposure.

Many intense optical sources also produce significant amounts of UVR which may be hazardous to the eye and skin. This hazard should be separately assessed, using UVR guidelines (ICNIRP 2004). It should be noted however, that the UVR guidelines do not take account of the photoretinopathy action spectra. The risk for photochemically induced photoretinopathy may be evaluated by applying the blue-light photochemical exposure limits given here.

Artificial lamps are used in many consumer and office appliances but, because of the need for visual comfort, these sources seldom pose a real hazard. Light-emitting diodes (LEDs) emit relatively narrow-band optical radiation, which may not evoke a strong aversion response. The special optical properties of lasers differ significantly from those of conventional, broad-band optical sources, and so the exposure limits for broad-band optical sources are necessarily expressed differently from those applicable to lasers. In addition, laser guidelines (ICNIRP 1996, ICNIRP 2000, IEC 2007) incorporate assumptions of exposure that may not apply to conventional optical sources. Most lasers emit radiation over one or more extremely narrow wavelength bands, and no detailed knowledge of the spectral output is required for purposes of hazard evaluation apart from the wavelength of the laser. By contrast, evaluation of the potential hazards of broad-band conventional light sources requires spectroradiometric data to apply several different photobiological action spectra, as well as knowledge of the exposure geometry. The action spectra are specific to different ocular structures.

5. BIOLOGICAL EFFECTS

The eye and skin are the organs most susceptible to damage by optical radiation. The type of effect, injury thresholds, and damage mechanisms vary significantly with wavelength (Fig. 1).

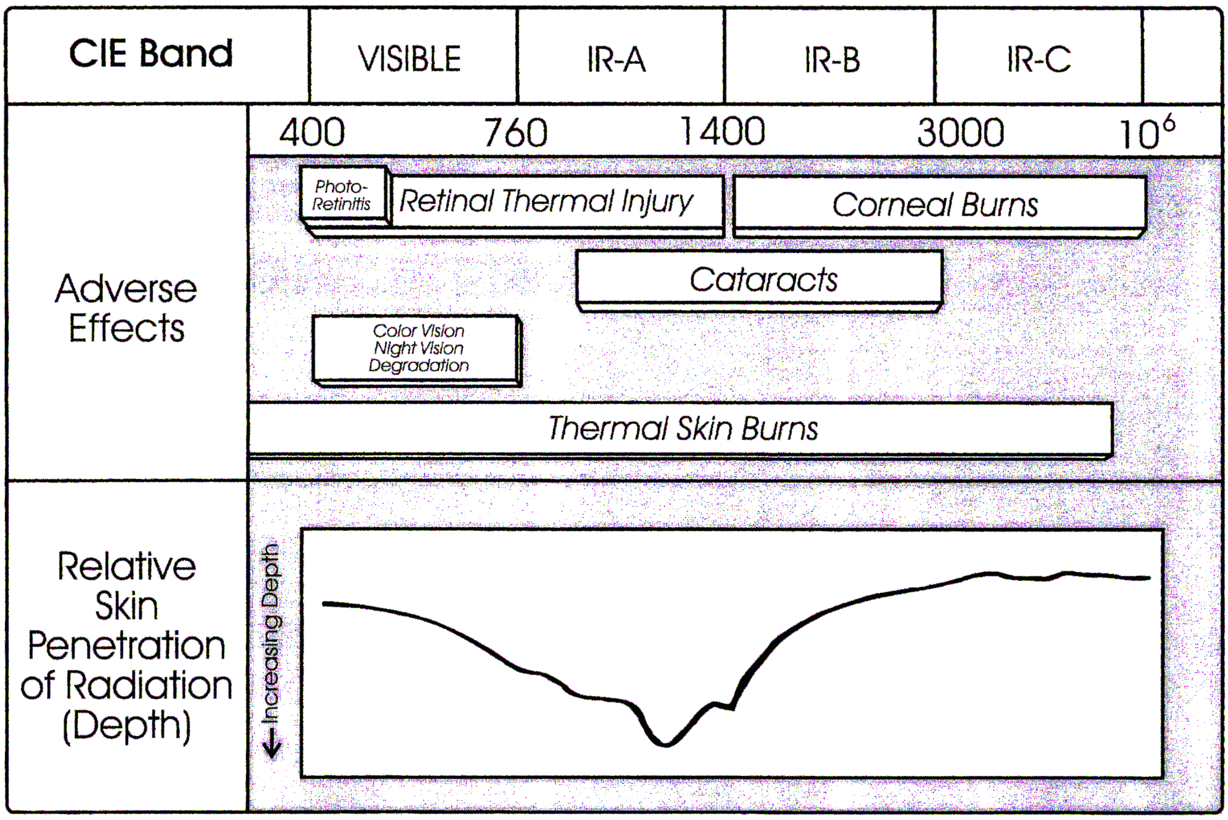

Fig. 1 Adverse biological effects and penetration depth of visible and infrared radiation.

The effects may overlap and must therefore each be evaluated independently. Action spectra exist for each effect.

5.1 Damage in the skin and eye

At least eight separate types of damage to the eye and skin may be caused by visible and infrared optical radiation:

Eye

1. Thermal damage of the cornea, approximately 1 400 nm - 1 mm
2. Thermal damage of the iris, approximately 380 nm – 1400 nm.
3. Near-infrared thermal damage of the crystalline lens, approximately 800 – 3 000 nm.
4. Thermal damage of the retina (380 – 1 400 nm).
5. "Blue-light" photochemical damage of the retina, principally 380 – 550 nm; 300 – 550 nm for the aphakic eye (Ham; Mueller; Sliney 1976, Ham Jr 1989, Lund; Stuck; Edsall 2006). This is also referred to as Type II photochemical retinal damage
6. Photochemical retinal damage from chronic exposure to bright light, Type I photochemical retinal damage, (Noell; Walker; Kang; Berman 1966, Mellerio 1994)

Skin

1. Thermal damage (burns) of the skin, approximately 380 nm - 1 mm,
2. Photosensitized damage of the skin, which is generally far more typical of UVR wavelengths (less than 380 nm), although such photosensitized reactions can extend to approximately 700 nm, possibly as a side-effect of certain medications (Fitzpatrick; Pathak; Harber; Seiji; Kukita 1974, Magnus 1976, Diffey 1982).

Ultraviolet radiation poses the primary known environmental risk factor for skin cancer. Visible radiation is not known to make additional contribution to risk (IARC 1992, UNEP; WHO; IRPA 1994, ICNIRP 2004, ICNIRP 2007).

5.1.1 Characteristics of photochemical interaction mechanisms

The threshold radiant exposure is subject to the principle of *reciprocity,* the Bunsen–Roscoe Law of Photobiology, stating that the effect depends only on the dose (the radiant exposure, i.e. the product of irradiance and exposure duration), but not (within certain limits) on the exposure duration. Thus, for example blue-light retinal injury (photochemically induced photoretinopathy) can result from viewing either an extremely bright light for a short time or a less bright light for a longer duration. Reciprocity helps to distinguish these effects from thermal injuries (see below). For photochemical injury of the retina, the sensitivity peaks at approximately 440 nm for the eye with an intact crystalline lens, a phakic eye (Ham; Mueller; Sliney 1976).

5.1.2 Characteristics of thermal interaction mechanisms

Thermal injury, unlike photochemical injury, does not show reciprocity between irradiance and exposure duration. Thermal injury is strongly dependent upon heat conduction from the irradiated tissue. It requires an intense exposure within seconds to cause tissue coagulation. When exposure is less intense, surrounding tissue conducts heat away from the exposed site. Thresholds for acute thermal injury of both cornea and retina in experimental animals have been corroborated for the human eye by flash burn accident data. Normally, a temperature of at least 45 °C is necessary to produce a thermal burn. Higher temperatures are required for thermal injury to result from exposures of shorter duration, e.g. about 59 °C for 10 s or 72 °C for 1 ms, (Figure 2) (Priebe; Welch 1978, Allen; Polhamus 1989, Schulmeister; Jean 2011b).

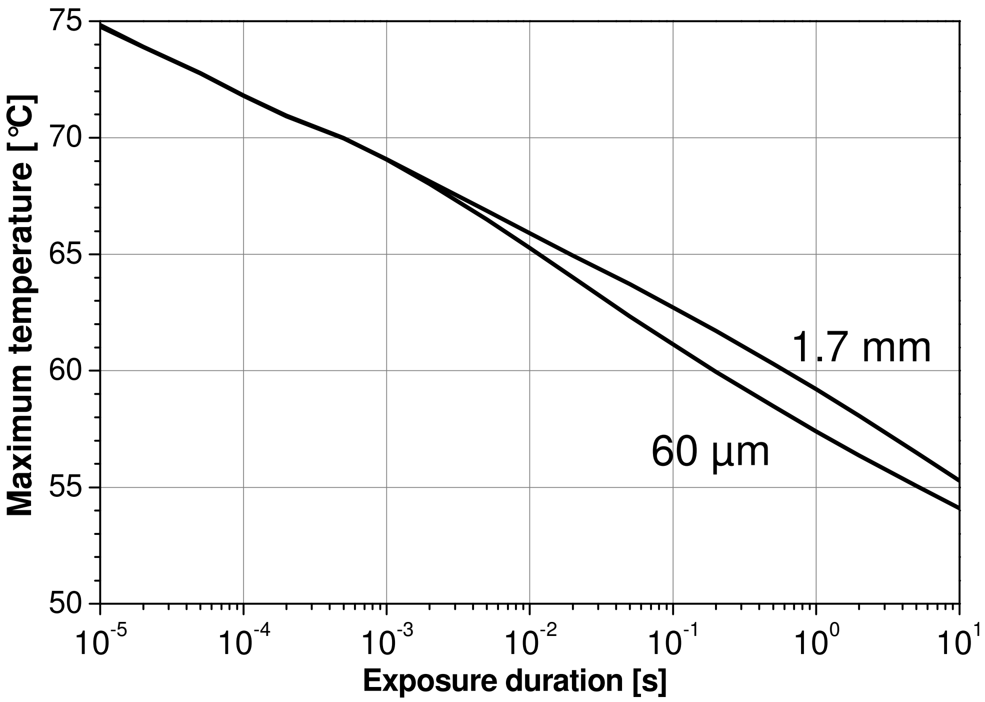

Figure 2 The calculated peak temperature rise (at the lesion radius) necessary to result in retinal thermal injury in a 60 μm and 1.7 mm retinal image as a function of duration of light exposure (Schulmeister; Jean 2011a).

For small images and pulse durations longer than about 10 ms, the steady state temperature is reached during the pulse and the temperature is at its maximum for longer periods during the pulse. Consequently, the critical temperature is somewhat lower than for larger images, for which the peak temperature is only reached at end of the pulse. Due to the strong non-linearity of thermal injury on temperature, the cooling phase after the cessation of the pulse has no influence on the critical temperature (Schulmeister; Jean 2011a).

The irradiance required to achieve these temperatures depends upon the ambient tissue temperature and the exposure spot size. Because of the more efficient cooling of small spots, injury of small spots requires higher irradiances than injury of large spots.

5.2 Retinal injury

The principal retinal hazard from viewing bright light sources is photochemically induced photoretinopathy, e.g. solar retinitis(Vos; van Norren 2001) with an accompanying scotoma from staring at the sun ("eclipse blindness") or from staring into a welding arc without proper eye protection (Uniat; Olk; Hanish 1986, Choi; Chun; Lee; Rah 2006). Laboratory studies demonstrated that photochemical injury from exposures of the order of ~10 s to 1-2 h duration is related to absorption by the retinal pigmented epithelium and choroid of short-wavelength light in the 380 – 520 nm region (Ham et al. 1978). This is usually referred to as blue-light hazard (Sliney; Wolbarsht 1980) but also as Type II photochemically induced retinal damage (Mellerio 1994). Small temperature rises in the retina may be synergistic with the photochemical process.

Animal studies demonstrated that continued exposures over several days to very bright light led to retinal injury (Noell; Walker; Kang; Berman 1966, Mellerio 1994), also referred to as Type I retinal photochemically induced damage. This type of damage has been suggested to be linked to direct damage of the photoreceptors due to bleaching.

Shorter-wavelength visible radiation has been suggested to accelerate retinal aging (Marshall 1983, Young 1988).

Only the very high radiance from sources such as a xenon-arc flash lamp, a nuclear flash or a laser is capable of producing *thermal* injury of the retina.

The mechanisms involved in thermal 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 380 –1 400 nm are well understood and supported with experimental threshold data, retinal explant data and models of thermal retinal injury (Mainster; White; Tips; Wilson 1970, Birngruber; Hillenkamp; Gabel 1985, Freund; McCally; Farrell; Sliney 1996, Lund; Edsall; Stuck; Schulmeister 2007, Schulmeister; Husinsky; Seiser; Edthofer; Fekete; Farmer; Lund 2008).

Although there are no clear boundaries between injury mechanisms, certain mechanisms dominate depending on the spectral region and the exposure duration. For short-duration, less than a few seconds, the damage is due to thermal injury. Photochemical, rather than thermal, effects dominate only in the wavelength region below approximately 600 nm for exposure times in excess of 10 s. At infrared wavelengths where photochemical effects have not been detected, thermal effects still dominate for exposure times longer than 10 s. Radial heat flow produces a strong dependence of retinal injury threshold on retinal image size. For small and medium retinal image sizes, eye movements affect the retinal photochemical injury thresholds by distributing the retinal radiant exposure over a larger area (Yarbus 1967, Naidoff; Sliney 1974, Sliney 1988);Sliney, 1989 #1957}.

5.3 Anterior segment injury

In the anterior segment of the eye, opacification of the cornea or the lens are the major effects of concern after exposure to infrared radiation. However, damage of the cornea is only possible if intense radiation is focused onto the cornea. For the lens, chronic exposure to high levels of infrared radiation potentially causes cataract. For exposure to intense pulsed light sources at close proximity to the eye, thermally induced damage of the iris is a concern.

Pitts and Cullen (Pitts; Cullen 1981) showed that the threshold exposures for lenticular changes caused by IR-A were of the order of 50 MJ m^{-2}. Threshold damage irradiances were at least 40 kW m^{-2}. (Wolbarsht 1978, Wolbarsht 1992) showed somewhat similar levels using an Nd:YAG laser operating at 1064 nm. Scott (Scott 1988b, Scott 1988a) showed that the calculated temperature rise was several degrees. Glass and steel workers exposed in hot environments to infrared irradiances of the order of 80- 400 mW·cm^{-2} daily for 10–15 years have reportedly developed lenticular opacities (Lydahl 1984).

5.4 Circadian rhythm regulation

Light has a profound impact upon circadian regulation of the human neural endocrine system (Brainard; Hanifin; Greeson; Byrne; Glickman; Gerner; Rollag 2001). A non-visual photoreceptor in the human retina (photoreceptive ganglion cells) mediates this response (Berson; Dunn; Takao 2002). The secretion of melatonin is suppressed by retinal exposure to short wavelength visible radiation. The implications for adverse health impacts remain speculative (Turner; Mainster 2008).

5.5 Visual disturbance

Temporary visual disturbances such as disability glare, discomfort glare, and after-images ("flash blindness") may be caused by brief exposures to bright light sources at levels below the exposure limits (Chisum 1973), and precautions should be taken against secondary safety hazards resulting from temporary reduction in vision.

5.6 Skin injury

Photosensitized injury of the skin by visible light is possible as a result of the presence of both endogenous and exogenous photosensitizers such as bilirubin and phenothiazine. Although this effect is far less likely to be caused by light than by UVR, it may occur with the ingestion of certain photosensitizing compounds in food or medicines (Fitzpatrick; Pathak; Harber; Seiji; Kukita 1974, Magnus 1976, Diffey 1982). For example, the action spectrum for porphyria frequently has secondary peaks at about 400 nm and 500 nm (Diffey 1982).

Thermal injury thresholds of the skin are highly dependent upon the size of the exposed area, perfusion, pigmentation and the initial skin temperature, which is usually 22 – 25 °C compared with 37 °C for the retina. Very high irradiances are needed to produce thermal injury within the pain reaction time, < 1 s (Hardy; Oppel 1937, Moritz; Henriques 1947, Stolwijk 1980). Higher temperatures (Henriques 1948) are required for thermal injury to result from exposures of shorter duration (e.g. about 47 °C for 10 s or 57 °C for 1 ms). In typical industrial situations, whole-body heat stress tends to limit the duration of exposure to optical radiation, keeping it below the threshold for thermal damage to the skin. Hence, only pulsed, or very brief, exposures to very high irradiances pose a thermal hazard to the skin. In addition, chronic exposure to heat is known to induce a fixed reddening of the skin not related to radiation erythema ab igne, which may be related to skin cancer (ICNIRP 2006).

5.7 Heat stress

Long-term whole body exposure below the thresholds for thermal damage to the eye and skin can overload the body's temperature regulating capacity and result in heat stress (ACGIH 2010).

6. BIOPHYSICAL BASIS FOR THE EXPOSURE LIMITS

Adverse biological effects of radiation are theoretically possible across the entire optical spectrum, but in the context of these guidelines there is particular concern about the visible and near-infrared regions, 380 – 1 400 nm where radiation can cause retinal injury. The photobiological hazards vary widely, with effects on the skin and on different parts of the eye being dependent on wavelength. Exposure to broadband (non-laser) optical sources that emit light and infrared radiant energy must therefore be evaluated applying several specific action spectra.

In developing exposure limits for broad-band optical sources, action spectra were specified and used to spectrally weight the exposure to derive a "biologically effective radiance or irradiance" that is compared to the exposure limits. This provides the most accurate hazard assessment. Exposure limits can then, independently of the source spectrum, be specified in terms of exposure duration and other relevant parameters, so that all sources are evaluated with the same risk criteria. Thus, for a given exposure, that is produced by a given source, at the eye and the skin, several action spectra may need to be applied. This may result in dissimilar effective irradiance and/or radiance. Also, for the determination of the effective radiance relevant for the blue light hazard, due to averaging field of views, the effective radiance may be smaller than the actual physical radiance. The different effective exposure levels are subsequently compared with the respective exposure limits.

This dosimetric concept reflects that for exposure to radiation from a given source, there may be more than one hazard, e.g. photochemically induced photoretinopathy *and* thermal damage to the lens.

6.1 Retina

6.1.1 Retinal image size and source size

In the wavelength range where the pre-retinal media of the eye are transparent (mainly 380 nm to 1400 nm), optical radiation is imaged onto the retina as is shown schematically in Figure 3.

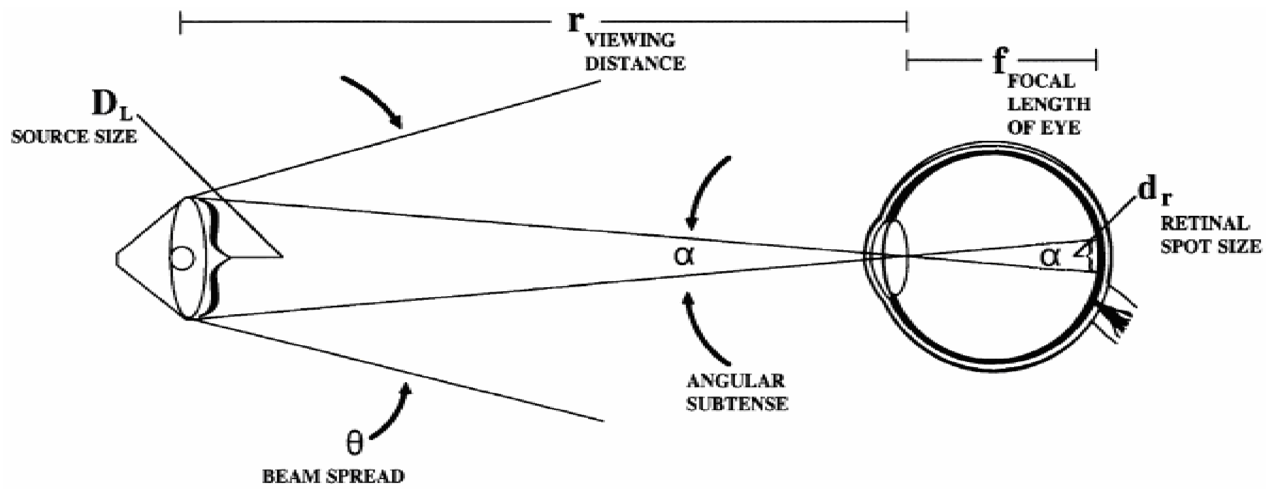

Figure 3 Geometry of ocular exposure and distinction between beam spread θ and angular subtense α

The focal length of the lens system of the human adult eye (cornea and lens) would for the case of focusing at infinity equal 17 mm, recalculated for the optical power of the eye surrounded by air (Gullstrand 1909). The angular subtense of the source, α (Figure 3) is the angle subtended by the actual light source (not the fixture) at the position of the eye. For the simplified assumption of the optical power of the eye surrounded by air, the angle subtended by the source is equal to the angle subtended by the image (Sliney; Wolbarsht 1980). For retinal images resulting from sources of small angular subtense (so that the angular subtense in units of radians is obtained by dividing the extent by the distance), the retinal image dimension, d_r (mm), is directly related to the source dimension, D_L, (mm), the effective focal length of the eye in air, f (i.e. 17 mm), and the viewing distance from the source, r (mm) (Eq. 1) (Sliney; Wolbarsht 1980).

$$d_r = D_L \cdot \frac{f}{r} \qquad \textit{Eq. 1}$$

The angular subtense of a source should not be confused with the beam spread, θ , of a collimated source, such as a searchlight, although under certain conditions (for a well collimated beam and when the source is projected to infinity by optics in front of the lamp) it is equivalent.

From knowledge of the optical parameters of the human eye and the radiometric parameters of a light source, it is possible to calculate irradiances at the retina, as shown below (Equation 2). In physiological optics, it is necessary to distinguish between a "point source" and an "extended source". A source is considered a point source if the angular subtense is less than or equal to α_{min}, where α_{min} equals 1.5 mrad, which corresponds to a retinal spot size of 25 µm. As an extended source is viewed at ever-increasing distance, it begins to behave as a point source and Equation 1 becomes invalid for image dimensions less than approximately 25–50 µm (Sliney; Wolbarsht 1980). For ease of application, the blue-light hazard exposure limits for extended sources and small (or "point") sources are expressed in different quantities. Radiance (W m^{-2} sr^{-1}) and integrated radiance (J m^{-2} sr^{-1}) are used for exposure limits derived to protect the retina. Irradiance (W m^{-2}) and radiant exposure (J m^{-2}) are generally used for exposure limits derived to protect the skin, the cornea, and the lens, and may also be used to express limits for the retina where minimal image sizes apply. If a circular measurement, field-of-view (γ_{meas}), is defined, over which the measured radiance is averaged or to which irradiance is limited, all of the retinal hazard limits can be expressed as radiance as well as irradiance. Radiance limits can then be reduced to an equivalent irradiance by multiplying by the solid angle Ω corresponding to γ_{meas}, i.e. by $\pi / 4 \cdot \gamma_{meas}^2$ (Henderson; Schulmeister 2004). The measurement conditions are discussed below.

6.1.2 Calculating retinal exposure

Retinal irradiance is directly related to source radiance, Ls (W m^{-2} sr^{-1}), (brightness), the transmittance of the ocular media, τ (rel), the pupil diameter, d_e (m), and inversely related to the effective focal length of the eye, f (m) (Eq. 2) (Sliney; Wolbarsht 1980, Henderson; Schulmeister 2004) .

$$E_r = \frac{\pi \cdot L_s \cdot \tau \cdot d_e^2}{4 \cdot f^2} \qquad \textit{Eq. 2}$$

It is *not* readily related to corneal irradiance.

For the visible spectrum, the transmittance in the ocular media for younger people, and most animals, is as high as 0.9 (Geeraets; Berry 1968). Using the effective focal length of the adult human eye, Gullstrand eye, *f* = 17 mm (Gullstrand 1909) the retinal irradiance is given by Eq. 3.

$$E_r = 2700 \cdot L_s \cdot \tau \cdot d_e^2 \qquad \textit{Eq. 3}$$

Eq. 3 assumes that the iris is pigmented and that the pupil acts as a true aperture. In albino individuals, however, the iris is not very effective, and some scattered light reaches the retina. Nevertheless, imaging of the light source still occurs, and Eq. 3 is valid if the contribution of scattered light, which falls over the entire retina, is added.

The distribution of the radiant energy in retinal tissues, that may lead to injury, depends not only on the retinal irradiance but also, very strongly, on radial heat flow and eye movements.

6.1.3 The effect of retinal heat flow

For retinal thermal injury, the thresholds vary with retinal image size because of the impact of radial heat flow on the temperature, in the centre of the image on the retina. Mathematical models and experimentally determined thresholds for retinal thermal injury show that threshold retinal irradiance varies more or less inversely as the image diameter for image diameters from approximately 25 µm to approximately 2 000 µm for exposure durations on the order of 1 second (Sliney; Wolbarsht 1980, Allen; Polhamus 1989, Courant; Court; Abadie; Brouillet 1989). For image diameters greater than 2 mm there is little or no variation of the retinal irradiance threshold with image diameter and a constant radiance threshold applies. Because of heat flow during the exposure, there is a dependence of the retinal injury threshold on retinal image size. This effect is greatest for longer duration exposures and is nearly non-existent for short-duration pulses of the order of 1 µs (Freund; McCally; Farrell; Sliney 1996, Framme; Schuele; Roider; Birngruber; Brinkmann 2004, Schuele; Rumohr; Huettmann; Brinkmann 2005, Schulmeister; Sliney; Mellerio; Lund; Stuck; Zuclich 2008).

6.1.4 The effect of eye movements

Continuous eye movements are of major significance in the derivation of the exposure guidelines, particularly for photochemically induced injury, and have smaller impact on thermally induced injury (Lund 2006). Eye movements effectively enlarge the irradiated retinal area and effectively increase the angular distribution of the energy on the retina. The extent of eye movements depends upon the viewing duration. For brief exposures, involuntary eye movements dominate (Ness; H.; Stuck; Lund; Lund; Molchany; Sliney 2000). For very long exposures of 1 000 seconds or more, when task-determined eye movements dominate, the angle is at least 100 mrad (Walker-Smith; Gale; Findley 1977, Yarbus 1977). Hence, the angle required for spatially averaging the radiance of a small source for comparison with the photochemical retinal limit is related to the angular extent of the eye movements. An averaging angle of 11 mrad is recommended for determination of exposure level for photochemical retinal effects and exposure duration less than 100 s. An averaging angle of 11 mrad represents minimal eye movements that can be associated with staring (fixating) a certain point. For exposure durations longer than of the order of 10 seconds, continued fixation of a point will usually only occur for special task where it is necessary to concentrate on a given point, such as for welding. Thus for exposure to optical radiation when it is not required to fixate a given point, the averaging angle of 11 mrad is a conservative value. For longer exposure durations, the extent of eye movements is not generally characterized and strongly depends on the task and behavior. As a conservative value, an averaging angle of 110 mrad is specified for exposure durations of 10 000 s (the maximum integration duration for the blue light hazard). If the visual task and the behavior can be characterized, a safety analysis can account for more realistic eye movements and use a larger averaging angle. The average angular fields of view of 11 mrad and 110 mrad correspond to retinal image dimensions of 200 µm, and 1.9 mm, respectively, at the retina.

6.1.5 Infrared exposure of the retina with low visual stimulus

A special exposure limit is required to protect the retina against thermal injury while viewing infrared LEDs or other specialized infrared illuminators with visible light removed by filters, which result in loss of the aversion response (Eq. 24) and where pupil constriction can not be assumed. This limit was derived assuming a 7 mm pupil and extending the trend of the exposure limit for pulses beyond 0.25 seconds. The long term exposure duration limit is based largely on the studies of Ham et al. (Ham; Mueller; Williams; Geeraets 1973), who studied thermal injury in infrared spectral bands.

6.2 Anterior structures of the eye

In addition to evaluating the retinal hazards, for many sources, assessment of potential thermal hazard to the anterior segment of the eye is essential. Contributions of IR-A (760 – 1 400 nm) and IR-B (1.4 – 3.0 µm) must be considered. Data on which to base exposure limits for chronic exposure of the anterior portion of the eye to infrared radiation are limited. Sliney and Freasier (Sliney; Freasier 1973) stated that the average corneal exposure from infrared radiation in sunlight is of the order of 10 W m^{-2}.

As previously noted, rapidly changing photochemical action spectra are characteristic of ultraviolet and short-wavelength light exposure, and spectral data are therefore important. However, because the infrared radiation effects are thought to be largely thermal, chronic infrared radiation exposures of the cornea and lens are not believed to involve rapid changes in spectral sensitivity (Barthelmess; Borneff 1959, Sliney 1986). Radiant energy absorbed in the cornea, aqueous humour, and iris is conduced, and some heating will occur in the lens regardless of the optical penetration depth. Penetration depth strongly varies in the IR-A and IR-B spectral bands, between 1.2 and 3 µm. However, this should have no great effect on the final temperature rise resulting from exposure to a continuous-wave source once thermal equilibrium is achieved. The final temperature of the lens also depends on the ambient temperature (Sliney 1986, Okuno 1991). For each degree that ambient temperature falls below 37 °C, an added radiant exposure of at least 6 W m^{-2} would be required to maintain the temperature of the lens (Stolwijk; Hardy 1977).

Vos and van Norren (Vos; Van Norren 1994) argued that an irradiance of 1 kW m^{-2} would not increase the temperature of the anterior segment of the eye by more than 1 °C. This level of irradiance on the face would be painfully warm and not tolerated.

UVR poses a serious hazard to the anterior segment of the eye. Therefore, for sources emitting UVR, the ICNIRP Guideline for UVR (ICNIRP 2004) should also be consulted.

6.3 Synergistic effects

The synergism between thermal and photochemical effects in the lens and retina has been studied in some experiments. Thermal enhancement of photochemical reaction has been experimentally demonstrated (Pitts; Cullen 1981, Allen; Polhamus 1989), although the effect is less than a factor of two; this has been taken into account in deriving the exposure limits by introducing a greater reduction factor.

6.4 Skin exposure

A realistic danger of thermal injury to the skin exists only in environments where a very high irradiance can be delivered from a pulsed source. ICNIRP provides guidance only for exposures lasting less than 10 s (based on empirical conservative assumptions).

For lengthier exposures, heat stress guidelines must be consulted. Most guidelines for control of heat stress are designed to limit deep-body temperature to 38 °C, and require consideration of air flow, ambient temperature, and humidity (ACGIH 2010).

6.5 Aversion Responses

The eye is adapted to protect itself against optical radiation from the natural environment, and humans have learned to use appropriate additional protective devices. Natural aversion response for exposure to bright light includes blinking, pupillary constriction, eye movements and squinting.

Gerathewohl and Strughold studied the blink reflex for full field exposure to flash lamps and determined that the shortest time from onset of the flash to full lid closure was 180 ms (Gerathewohl; Strughold 1953) The potential hazard of longer durations is essentially nullified by involuntary eye movements which distribute the light energy over a much greater area of the retina, and by behavioural reactions such as movement of the head (Fender 1964, Yarbus 1967). Reduction of the pupil size due to exposure to bright light dynamically reduces the retinal exposure for long duration exposure (Figure 4) (Stamper; Lund; Molchany; Stuck 2002).

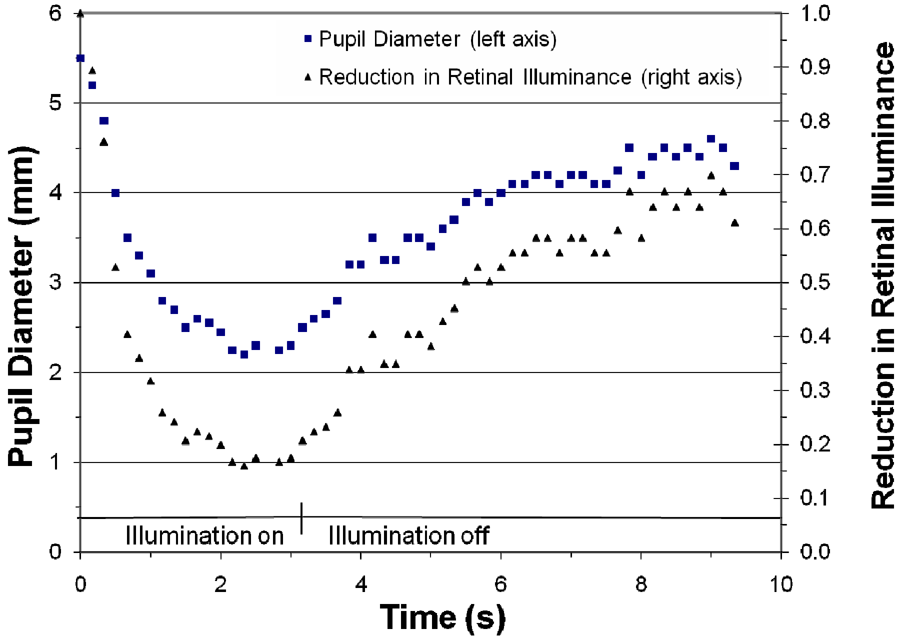

Figure 4 Dynamics of the pupillary constriction and reopening (squares - left axis) after 3 second exposure to a bright light and the reduction of the retinal illuminance due to pupil diameter change (triangles – right axis). The initial pupil diameter was 5.5 mm. Adapted from (Stamper et al. 2002)

The effect of eye movements on time-averaged retinal irradiance is illustrated by (Ness; Zwick; Stuck; Lund; Sliney 1999) and (Lund 2006).

Elevated temperatures of the skin and cornea produce an avoidance response within a few seconds temperatures that induce pain sensation (Randolph; Stuck 1976) are somewhat below the temperatures that lead to thermal injury (Henriques 1948). This usually induced an avoidance response within a few seconds that prevents a burn, with the exception of very high irradiances that rapidly heat the skin. Under the influence of alcohol and some medications the pain sensation might be decreased.

7. RATIONALE

The exposure limits were derived on the basis of current knowledge on damage thresholds and in accordance with the ICNIRP principles (ICNIRP 2002). The exposure limits are set to a level below the damage thresholds by applying a reduction factor. In view of uncertainties inherent in the damage thresholds, a reduction factor of at least two has been applied in deriving the exposure limits. In addition, simplification of wavelength, exposure duration and/or spot size dependence of the exposure limits compared to the respective trends of the injury thresholds has in many cases implicated higher reduction factors, occasionally as high as approximately two orders of magnitude.

The exposure limits derived for the eye are the most restrictive due to higher sensitivity of the eye compared to the skin. The consequences of overexposure of the eye are also generally more serious than those of overexposure of the skin, and safety standards for optical sources, including lasers, have therefore emphasized protection of the eye (UNEP; WHO; IRPA; WHO 1982, Duchêne; Lakey; Repacholi 1991, Health Council of the Netherlands 1993, ICNIRP 1996, ICNIRP 1997, ICNIRP 2000, ACGIH 2010).

The guidelines are based predominantly on ocular injury in animal studies and on human retinal injuries resulting from viewing the sun and welding arcs. The exposure limits also contain an underlying assumption that most outdoor environmental exposures to visible radiant energy are not normally hazardous to the eye except in environments producing reflections from surfaces such as snow and sand.

Exposure conditions that in animal experiments led to retinal damage Type I were extreme and far exceed those experienced by humans with broadband sources. Therefore no special exposure limits are recommended.

Injury of the skin following photosensitization is highly dependent on the photosensitizer and therefore must be treated according to toxicological criteria which is out of the scope of these guidelines.

The mechanical disruption of tissue caused by ultra-short laser pulses does not occur with current non-laser sources and is therefore not considered in the derivation of these guidelines.

For all currently known arc and incandescent sources, the contribution made by the far infrared radiation, 3 - 1 000 µm, is normally of little or no practical concern (ICNIRP 2006). Only lasers pose potential hazards in this spectral region. Thus, far infrared radiation can be largely ignored when a risk assessment for non laser-sources is made. Therefore, no exposure limits were recommended for this wavelength band. Normally, considerations of heat stress will dominate the risk assessment for conditions where there is significant IR-C.

Including the IR-C component in the determination of the exposure would constitute a conservative risk assessment analysis when the total IR radiation is compared to the exposure limits for protection of the anterior parts of the eye (cornea and lens) and for protection against thermal injury of the skin.

A more detailed rationale for the changes of the exposure limits compared to previous guidelines (ICNIRP 1997) is given in the Appendix.

8. EXPOSURE LIMITS

Correct application of the exposure limits requires a knowledge of the spectral radiance, L_λ,, or spectral irradiance, E_λ, and depending on the source, the angular subtense of the source as it would be perceived by the eye. For a white-light source, such detailed spectral data are generally required only if the luminance exceeds 10^4 cd·m^{-2}. This rule-of-thumb results in an exclusion the majority of simple light sources, since these do not exceed the exposure limits for the retina.

In the derivation of the guidelines for retinal exposure, two different pupil diameters were assumed, 7 mm for the dark-adapted eye and approximately 3 mm for bright light conditions. Two limits are applied to protect against retinal thermal injury. There is one limit for the general case, broad-band sources which emit visible radiation, assuming a 7 mm pupil up to approximately 0.5 s, and thereafter due to pupillary constriction a 3 mm pupil. There is a second limit for infrared sources without a strong visual stimulus, assuming a 7 mm pupil.

If there is concern about longer exposures resulting from determined visual effort, the exposure limits for longer durations may apply. For exposure conditions where there is loss of the aversion response because of reduced visual sensitivity or surgical anesthesia ICNIRP provides recommendations for adjustment of exposure limits (Sliney; Aron-Rosa; DeLori; Fankhauser; Landry; Mainster; Marshall; Rassow; Stuck; Trokel; Motz-West; M. 2005).

Biological weighting functions are required to express the exposure limits for these types of injury (Figure 5, Table 2).

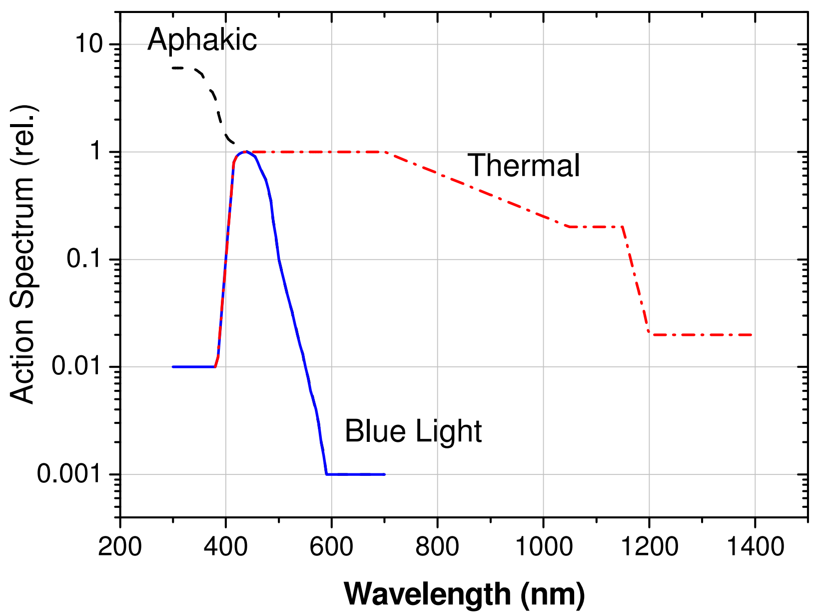

Figure 5 Action spectra for blue-light photoretinopathy for the rhesus monkey with lens (phakic) and without lens (aphakic), and for thermal photoretinopathy.

Table 2 Retinal hazard spectral weighting functions

Wavelength (nm)	Aphakic* hazard function $A(\lambda)$	Blue-light* hazard function $B(\lambda)$	Retinal thermal hazard function $R(\lambda)$
300	6.00	0.01	-
305	6.00	0.01	-
310	6.00	0.01	-
315	6.00	0.01	-
320	6.00	0.01	-
330	6.00	0.01	-
335	6.00	0.01	-
340	5.88	0.01	-
345	5.71	0.01	-
350	5.46	0.01	-
355	5.22	0.01	-
360	4.62	0.01	-
365	4.29	0.01	-
370	3.75	0.01	-
375	3.56	0.01	-
380	3.19	0.01	0.01
385	2.31	0.0125	0.0125
390	1.88	0.025	0.025
395	1.58	0.050	0.05
400	1.43	0.100	0.1
405	1.30	0.200	0.2
410	1.25	0.400	0.4
415	1.20	0.800	0.8
420	1.15	0.900	0.9
425	1.11	0.950	0.95
430	1.07	0.980	0.98
435	1.03	1.000	1.0
440	1.000	1.000	1.0
445	0.970	0.970	1.0
450	0.940	0.940	1.0
455	0.900	0.900	1.0
460	0.800	0.800	1.0
465	0.700	0.700	1.0
470	0.620	0.620	1.0
475	0.550	0.550	1.0
480	0.450	0.450	1.0
485	0.400	0.400	1.0
490	0.220	0.220	1.0
495	0.160	0.160	1.0
500	0.100	0.100	1.0
505	0.079	0.079	1.0
510	0.063	0.063	1.0
515	0.050	0.050	1.0
520	0.040	0.040	1.0
525	0.032	0.032	1.0
530	0.025	0.025	1.0
535	0.020	0.020	1.0
540	0.016	0.016	1.0
545	0.013	0.013	1.0

550	0.010	0.010	1.0
555	0.008	0.008	1.0
560	0.006	0.006	1.0
565	0.005	0.005	1.0
570	0.004	0.004	1.0
575	0.003	0.003	1.0
580	0.002	0.002	1.0
585	0.002	0.002	1.0
590	0.001	0.001	1.0
595	0.001	0.001	1.0
600-700	0.001	0.001	1.0
700-1 050	-	-	$10^{(700-\lambda)/500}$
1 050-1 150	-	-	0.2
1 150-1 200	-	-	$0.2 \cdot 10^{0.02\,(1150-\lambda)}$
1 200–1 400	-	-	0.02

*The UVR extension of $A(\lambda)$ and $B(\lambda)$ at wavelengths below 380 nm are provided for the evaluation of optical spectra that may contain UV.
The aphakic hazard function, $A(\lambda)$, requires normalization to a number >1 to correlate with the phakic hazard function, $B(\lambda)$.

8.1 Retinal thermal hazards (380–1,400 nm)

Protection of the human retina from thermal injury requires that the spectrally weighted radiance, or radiance dose, does not exceed the retinal thermal exposure limit. The retinal thermal injury spectrally weighted radiance, L_R ($W \cdot sr^{-1}\ m^2$), that is compared with the exposure limit for retinal thermal injury, is the spectral radiance, L_λ, ($W \cdot sr^{-1}\ m^2 \cdot nm$) weighted by the biological spectral efficiency, $R(\lambda)$ (Rel.), where λ (nm) is the wavelength (Eq. 4).

$$L_R = \sum_{380}^{1400} L_\lambda \cdot R(\lambda) \cdot \Delta\lambda \qquad \textit{Eq. 4}$$

The effective retinal thermal damage radiance dose, D_R ($J \cdot sr^{-1}\ m^2$) is obtained by integrating L_R over exposure time, t (s). The choice of $\Delta\lambda$ should be selected based on the wavelength dependence of the radiance and in regions where the biological spectral efficiency changes rapidly with wavelength.

8.1.1 Angular subtense of the source

In terms of the angular subtense of the source α, subtended at the point of exposure of the eye (Figure 3), large sources, where $\alpha \geq \alpha_{max}$, can be distinguished from intermediate sources where $\alpha < \alpha_{max}$ and where α is larger than 1.5 mrad. When the source appears under an angle of less than 1.5 mrad, it is referred to as point source. At distances where exposure to spatially incoherent radiation can produce a retinal thermal injury, the source is either intermediate or large.

The exposure limit is a function of the angular subtense, α.

For a non-circular source, α is the arithmetic mean of the shortest and longest dimension. When determining the arithmetic mean, each of the shortest and longest dimension, respectively, should be limited to α_{max}.

When the angular subtense α is larger than a critical angle α_{max}, the retinal thermal exposure limit no longer depends on the angular subtense α. The value of α_{max} depends on the pulse duration (exposure duration) *t*, (Table 3). In the tables and equations below, t refers to the exposure duration in seconds.

Table 3 Dependence of the maximum angular subtense, α_{max}, on exposure duration.

Exposure duration	Maximum angular subtense α_{max}
$t < 625\ \mu s$	0.005 rad
$625\ \mu s \le t < 0.25$ s	$\alpha_{max} = 0.2 \cdot t^{0.5}$ rad
$t \ge 0.25$ s	0.1 rad

8.1.2 Measurement of radiance

When assessing spatially irregular sources, or sources with hot spots, the radiance shall be averaged over an angle, γ_{th}, that depends upon the pulse (exposure) duration. For a continuous wave (CW) source, i.e. pulse durations equal to or greater than 0.25 s, γ_{th} equals 11 mrad. For pulsed sources, i.e. exposure durations shorter than 0.25 s, for the case that there are radiance hotspots, radiance should be determined with an angle of acceptance of γ_{th} equals 5 mrad. If the source is smaller than these γ_{th} and radiance is averaged over these values, the value of α in the retinal thermal exposure limit shall not be less than γ_{th}.

8.1.3 Large sources

Large sources are defined as sources with an angular subtense greater than α_{max}, (for α_{max} see Table 3). The limits for large sources also provide a conservative limit for smaller sources.

For pulse durations less than 1 µs, the EL is a constant radiance dose (Eq. 5).

$$D_R \le 126\ J\ m^{-2}\ sr^{-1} \qquad \textit{Eq. 5}$$

For exposure durations, t, from 1 µs to 625 µs, the weighted radiance or radiance dose must not exceed the values given in Eq. 6.

$$D_R \leq 4.0\ t^{0.75}\ kJ\ m^{-2}\ sr^{-1} \qquad \textit{Eq. 6}$$

t in seconds

For viewing durations between 0.625 ms and 0.25 s, the limit is given by Eq. 7.

$$t \cdot L_R \leq 100\ t^{0.25}\ kJ\ m^{-2}\ sr^{-1} \qquad \textit{Eq. 7}$$

t in seconds

Since a 7 mm diameter pupil, i.e. a dark-adapted pupil is assumed for pulsed sources, the retinal thermal exposure limit (EL) is conservative for a normal, reactive pupil under daylight conditions in which the pupil will be less than 7 mm in diameter. Nevertheless, the EL should not be modified for daylight conditions unless pathological pupillary reactions have been excluded.

For viewing durations greater than 0.25 s, the exposure limit is given by Eq. 8

$$L_R \leq 280\ kW\ m^{-2}\ sr^{-1} \qquad \textit{Eq. 8}$$

8.1.4 Intermediate sources

Intermediate sources are defined as sources with an angular subtense, α, greater than α_{min} and less than α_{max} (Table 3). For intermediate sources, the retinal thermal injury limit depends on both the exposure duration t (in s) and the angular subtense of the source (in rad) subtended at the point of exposure.

For pulse durations less than 1 µs, and $\alpha < \alpha_{max}$, , the exposure limit is given by Eq. 9.

$$\cdot \quad = \sum_{\lambda} \cdot \quad \lambda \ \cdot \Delta\lambda \leq \quad - \quad - \ 625\ \alpha^{-1}\ J \cdot m^{-2}\ sr^{-1} \qquad \textit{Eq. 9}$$

t in seconds, in rad

For viewing durations between 1 µs and 0. 25 s and $\alpha < \alpha_{max}$ (Table 3), the exposure limit is given by Eq. 10.

$$t \cdot L_R \leq 20\ \alpha^{-1}\ t^{0.75}\ kJ\ m^{-2}\ sr^{-1} \qquad \textit{Eq. 10}$$

t in seconds, α in rad

For viewing durations greater than 0.25 s, when $\alpha < \alpha_{max}$, the exposure limit is given by Eq. 11.

$$L_R \leq 28\ \alpha^{-1}\ kW\ m^{-2}\ sr^{-1} \qquad \textit{Eq. 11}$$

α in rad

There may be special individual circumstances where the pupil remains dilated (tonic) and exposures extend beyond 0.25 s, e.g., during some ophthalmic examination procedures (Sliney; Aron-Rosa; DeLori; Fankhauser; Landry; Mainster; Marshall; Rassow; Stuck; Trokel; Motz-West; M. 2005). Under these unusual conditions, Eq. 12 should be applied for $\alpha \leq \alpha_{max}$.

$$L_R \leq 20\ \alpha^{-1}\ t^{-0.25}\ kW\ m^{-2}\ sr^{-1} \qquad \textit{Eq. 12}$$

t in seconds, α in rad

8.1.5 Protection of the anterior segment of the eye

For sources in contact or immediate proximity to the eye, it holds that for short pulses and large sources at levels approaching the thermal retinal exposure limits, injury to the anterior segment of the eye can not be excluded. However without additional research, a specific exposure limit cannot be stated. In the absence of specific guidance, the infrared exposure limits for the anterior parts of the eye section 8.4.1 will provide a conservative guideline when also applied to the visible spectral range.

8.2 Blue-light photochemical retinal hazard

For protection of the retina against acute photochemically induced photoretinopathy, the effective blue-light radiance dose has to be limited. The effective blue-light radiance dose, D_B (J·sr^{-1} m^{-2}), is a function of the spectral radiance of the source, L_λ ($W \cdot sr^{-1}\ m^{-2}$) weighted with the blue-light hazard function, *B(λ)* (Rel.) and the exposure time, *t* (s), (Eq. 13)

$$D_B = \sum_{300}^{700} L_\lambda \cdot B(\lambda) \cdot t \cdot \Delta\lambda \quad \text{or} \qquad \textit{Eq. 13}$$

$$L_B \cdot t = \sum_{300}^{700} L_\lambda \cdot B(\lambda) \cdot t \cdot \Delta\lambda$$

For *t* < 10 000 s (approx. 2.8 hours), the effective blue light radiance dose is limited to the value given in Eq. 14.

$$D_B \le 1.0\ MJ \cdot m^{-2} \cdot sr^{-1} \qquad \textit{Eq. 14}$$

For non-constant radiance values, intermittent or pulsed exposure, the effective blue light radiance dose, D_B ($J \cdot sr^{-1}\ m^{-2}$), is obtained by integration of L_B over time t.

For *t* > 10 000 s, the exposure limit for blue light expressed as effective blue light radiance is given in Eq. 15.

$$L_B \le 100\ W \cdot m^{-2} \cdot sr^{-1} \qquad \textit{Eq. 15}$$

The limit for L_B refers to a spatially averaged radiance over an angle, γ_{ph}.

The averaging angle of acceptance, γ_{ph}, varies according to Eq. 16, Eq. 17 and Eq. 18.

$$\gamma_{ph} = 11 \quad mrad \quad for \le 100\ s \qquad \textit{Eq. 16}$$

$$\gamma_{ph} = 1.1 \cdot t^{0.5}\ mrad \quad for \quad 100 < t < 10,000\ s \qquad \textit{Eq. 17}$$

$$\gamma_{ph} = 110 \quad mrad \quad for\ t > 10,000\ s \qquad \textit{Eq. 18}$$

For sources where the angular subtense, α, is less than γ_{ph}, the radiance limit can be converted to an equivalent irradiance or radiant exposure limit for a given duration, *t,* that is compared to effective radiant exposure or irradiance values determined with an 'open' field of view (Schulmeister 2001). This is often easier to measure than averaged radiance. The potential hazard may be evaluated by mathematically weighting the spectral irradiance, E_λ, against the blue-light hazard function to obtain E_B (the effective radiant exposure H_B is obtained by integrating the effective irradiance E_B over the exposure duration). The limits for the blue-light hazard expressed as radiant exposure and irradiance, applicable to sources that are smaller than the angle of acceptance γ_{ph}, (Eq. 16-Eq. 18) are given in Eq. 19, Eq. 20.

$$10\ s\ to\ 100\ s:\ H_B \le 100\ J\ m^{-2} \qquad \text{Eq. 19}$$

$$100\ s\ to\ 30\ 000\ s:\ E_B \le 1\ W\ m^{-2} \qquad \text{Eq. 20}$$

In effect, because of eye movements involved in normal visual tasks, a maximal duration of concern for small bright sources is 100 s. Hence, for exposure durations longer than 100 s, the small source limit expressed in irradiance is constant.

Notice that when the irradiance measurement is performed with the angle of acceptance as specified in equations Eq. 16-Eq. 18 (which for the case of irradiance is not an averaging angle but a limiting angle of acceptance), the limits specified in Eq. 19, Eq. 20.can also be applied to sources larger than the specified angle of acceptance and are fully equivalent to the limits specified as radiance.

8.3 Retinal photochemical hazard to the aphakic eye and the infant eye (300-700 nm)

The third type of retinal hazard, the aphakic photochemical retinal hazard, is encountered very rarely. Therefore, guidance for this hazard is provided in the Appendix (12.2. Retinal photochemical hazard to the aphakic and infant eye)

The lens in infants aged less than two years transmits more ultraviolet than the adult lens and more protection is needed for the developing retina. Thus, the *A(λ)* weighting function should be used for a conservative hazard assessment of light sources to which infants are exposed.

8.4 Infrared radiation hazards to the eye

8.4.1 Cornea and lens (780–3000 nm)

To avoid thermal injury of the cornea and possible delayed effects on the lens of the eye (cataractogenesis), infrared irradiance E_{IR} (Eq. 21) in the wavelength range of 780 nm - 3 µm, should be limited (Eq. 22, Eq. 23).

$$E_{IR} = \sum_{780}^{1000} 0.3\, E_\lambda + \sum_{1000}^{3000} E_\lambda \qquad \textit{Eq. 21}$$

$$E_{IR} \le 18 \cdot t^{-0.75}\ kW\, m^{-2}\ \ (for\, t < 1\,000\, s) \qquad \textit{Eq. 22}$$

t in seconds

and

$$E_{IR} \le 100\ W\, m^{-2}\ \ (for\, t \ge 1\,000\, s) \qquad \textit{Eq. 23}$$

In cold environments, the long-term exposure limits may be increased to 40 mW cm^{-2} at 0 °C and approximately 30 mW cm^{-2} at 10 °C without the lenticular temperature exceeding 37°C. The relaxation of the limits is based on environmental heat exchange rates for the head (Stolwijk; Hardy 1977), the final temperature of the lens being calculated from ambient temperature.

8.4.2 Retina

For an infrared heat lamp or any near-IR source that provides no strong visual stimulus, the near-IR, IR-A (780–1 400 nm), should be limited as given in Eq. 24.

$$\sum_{780}^{1400} L_\lambda \cdot R(\lambda) \cdot \Delta\lambda \le 20\ \alpha^{-1}\ t^{-0.25}\ kW\, m^{-2}\, sr^{-1}\ \ (0.25\, s < t < 810\, s) \qquad \textit{Eq. 24}$$

For comparison with the EL, and for the case that the source exhibits hotspots, the radiance should be averaged over angles, γ_{th} = 11 mrad and the value of α is limited to values larger than 11 mrad.

For exposure durations less than 0.25 s, Eq. 5 applies.

8.5 Visible and infrared thermal injury to the skin

To protect the skin from thermal injury, the radiant exposure for durations less than 10 s should be limited as given in Eq. 25.

$$H = 20\,t^{0.25}\ kJ \cdot m^{-2} \qquad \textit{Eq. 25}$$

t in seconds

No limit is provided for longer exposure duration, as normal avoidance behavior will impose limits on duration of exposure. Much longer exposure durations are dominated by concerns of heat stress, and the reader is referred to the appropriate guidelines (European Committee for Standardization 1997, European Committee for Standardization 2004, ISO 2004 -a, ISO 2004 -b, ACGIH 2010).

Thermal pain is induced by skin temperatures which are lower than the temperatures needed to produce a thermal burn, and this pain would limit the exposure so that a thermal injury is prevented.

8.6 Repetitive Pulse Exposure

For exposure to repetitive pulses, intermittent exposure, or non-constant exposure levels, the following applies:

For photochemically initiated retinal injury, only the accumulated exposure for the applicable integration duration at the tissue of concern is the relevant exposure level, independent of the temporal nature of the exposure. The applicable integration duration is either the maximum anticipated exposure duration or 10 000 s, whichever is shorter.

Considerations of available biological data and mathematical models of thermal damage indicate that any exposure must be maintained below the single pulse exposure limit and below the exposure limit for the total duration of the train. For irregular pulse trains (with varying pauses between pulses and/or varying pulse duration or pulse peak power), any subgroup of pulses within the train must be analyzed to assure that no group of pulses exceeds the exposure limit for the total duration of the sub-group.

Thus, the following considerations apply to repetitive pulses or intermittent exposure

- First consideration: Single pulse exposure limit for thermal damage.

The exposure from any single pulse in a train of pulses shall not exceed the exposure limit for exposure times equal to the pulse duration.

- Second consideration: Pulse groups within a pulse train.
  The exposure from any group of pulses (or sub-group of pulses in a train) delivered in a time interval within the train should not exceed the exposure limit for that time interval within the train (subgroups of pulses are treated in the analysis as if they were single pulses).
- Third consideration: Average irradiance limitation.
  The average irradiance for the total length of the pulse train, T, should not exceed the exposure limit for either thermal or photochemical hazards, applicable to a continuous exposure of duration T.
- Fourth consideration: For pulse repetition frequencies exceeding 5 Hz and for extended sources ($\alpha > \alpha_{min}$), the retinal thermal limit for single pulses (the first and second consideration) has to be reduced as follows: for the case that the angular subtense of the source α is smaller or equal to α_{max} by a factor of 2.5; for the case that the angular subtense α is larger than α_{max}, by a factor of 5. These factors are simplified and over restrictive for the case of small number of pulses and can, for a less restrictive analysis, be replaced by a multiplication factor $n^{-0.25}$ that is limited to 1/2.5 for the case of $\alpha \le \alpha_{max}$ and 1/5 for the case of $\alpha > \alpha_{max}$ where n is the number of pulses within the maximum anticipated exposure duration.

9. APPLYING THE LIMITS

9.1 Exposure distance

For an analysis, the exposure of the eye and skin at the position of exposure is compared to the respective exposure limit.

For small sources, such as an optical fiber, the closest distance at which the human eye can sharply focus is about 100– 200 mm. A viewing distance of 100 mm requires extreme near-point accommodation and really applies only to small children and to very myopic individuals. Therefore, 100 mm viewing distance is generally only applied for worst-case assessment of point-source divergent beam lasers sources. For evaluation of both the retinal thermal hazard and the blue-light photochemical hazard, a closest viewing distance of 100-200 mm from the apparent source can therefore be assumed to represent the worst-case exposure.

At shorter distances, the image of a light source would be out of focus and blurred. In most situations, such short viewing conditions are unrealistic. A twenty centimeter worst-case assessment distance is realistic for conventional lamp sources (including LEDs). For example 0.5 m would be appropriate for arc welding, or 1 m or more for most lamps. Viewing distance could also be based upon considerations of the source luminance and ambient illumination.

9.2 Determination of exposure level

For localized exposures to inhomogeneous irradiance profiles, ICNIRP recommends an averaging aperture with a diameter of 7 mm. For homogenous irradiance profiles, the measurement aperture can be larger.

For comparison with skin exposure limits, the receptor should have a cosine response.

For comparison with retinal photochemical exposure limits specified in radiance or radiance dose, radiance or radiance dose has to be averaged over the angle of acceptance of γ_{ph}. The usage of γ_{ph} provides a spatially averaged radiance that accounts for eye movements (Schulmeister 2001). A specific angle of acceptance (field of view) can be accomplished either by using telescopic receiving optics on the instrument to limit the field of view to γ_{ph}, or by placing, as close as possible to the light source, an opaque baffle with an aperture that subtends an angle of γ_{ph} as seen by the detector. For example, a circular aperture of 11 mm diameter placed over a lamp source will subtend an angle of 11 mrad at a distance of 1 m. The angle of acceptance, γ_{ph} , varies with the exposure duration and is defined in Eq. 16, Eq. 17 and Eq. 18.

For comparison with the retinal thermal exposure limits, the acceptance angle can be important if the source has localized radiance hotspots. For pulsed sources with hot-spots, an angle of acceptance of 5 mrad should be used. For cw sources, the angle of acceptance does not have to be less than 11 mrad. If no hot spots are present, the angle of acceptance can be larger. See also 7.1.2

For comparison with limits to protect the anterior segments of the eye, radiation outside of a field of view of 80 ° does not need to be collected due to protection by the eye lids.

For all currently known arc and incandescent sources, the contribution made by the IR-C spectral region (3–1 000 µm) is normally of no practical concern. Thermal detectors without a filter (e.g. without a glass entrance window) can detect this radiant energy. If there are concerns about a far-infrared source, an unfiltered, open thermal detector measurement should be made to assess skin and corneal hazards, and irradiance may be averaged over an aperture of 10–50 mm for lengthy exposures.

10. PROTECTIVE MEASURES

The most effective hazard control is total enclosure of the light source. In circumstances where such containment is not possible, partial beam enclosure, eye protectors, administrative controls, and restricted access to intense sources may be necessary (Hietanen; Hoikkala 1990, Hietanen 1991).

Safety standards for welding have been developed worldwide (Sliney; Wolbarsht 1980, UNEP; WHO; IRPA; WHO 1982, Sutter 1990, European Committee for Standardization 2004, ANSI 2009).

11. PRODUCT SAFETY STANDARDS

Lamp safety standards have been developed which make use of a risk group classification scheme to permit specification of control measures based upon risk posed by the light source (IESNA/ANSI 2005, CIE 2006, IEC 2007). The emission limits in the product safety standards are generally derived from the ICNIRP and the ACGIH guidelines (ACGIH 2010). IEC and ISO also issue product safety standards for specific product groups which may contain limitations of the emission of optical radiation (IEC 2009, ISO 2010).

12. APPENDIX

12.1 Rationale for the changes since the previous guideline

Since the publication in 1997 of the ICNIRP Guidelines for Broadband Incoherent Optical Radiation (ICNIRP 1997) to limit exposures that may pose a retinal thermal hazard, further research has taken place with regard to the temporal, spatial and wavelength dependence of retinal thermal injury.

12.1.1 Spot size dependence

Because of heat flow during the exposure, there is a dependence of the retinal injury threshold on retinal image diameter ("spot-size"). This effect is greatest for longer duration exposures and is nearly non-existent for short-duration pulses of the order of 1 µs or less (Schuele; Rumohr; Huettmann; Brinkmann 2005, Zuclich; Lund; Stuck 2007, Schulmeister; Husinsky; Seiser; Edthofer; Fekete; Farmer; Lund 2008). Two domains need to be distinguished in terms of the dependence of the exposure limits on the angular subtense of the source, α: for values smaller than a critical angle, the exposure limit expressed as radiance or radiance dose depends linearly on the inverse of the angular subtense of the source α (Sliney; Wolbarsht 1980, Ham Jr 1989). This dependence reflects the fact that larger retinal irradiance patterns exhibit reduced radial cooling as compared to smaller ones. For values of the angular subtense of the source larger than this critical angle the exposure limit no longer depends on the angular subtense of the apparent source. This results because the retinal irradiance pattern is large compared to the heat diffusion distance during the pulse so that the center of the retinal irradiance pattern is not affected by radial heat flow during the pulse. It was known from physical principles and from short pulsed laser threshold studies (Zuclich; Lund; Stuck 2007) that for short pulses (where heat flow is negligible during the pulse), there is no spot size dependence. However, as a conservative simplified approach, the inverse spot size dependence in the previous exposure limits was applied up to a critical angle of 100 mrad. Recent thermal model and ex-vivo studies (Schulmeister; Husinsky; Seiser; Edthofer; Fekete; Farmer; Lund 2008) provided for a more complete understanding of the pulse duration dependence of the spot size dependence of retinal thermal injury. This allows for the formulation of a time dependent critical angle to better reflect the retinal irradiance diameter dependence for pulsed sources (Schulmeister 2007). The value of 100 mrad still applies for exposure to cw sources, i.e. for exposure durations larger than 0.25 s.

With the more complete understanding of the temporal trend of the spot size dependence, it was possible to more accurately define the exposure limits.

Pupillary reaction was not considered in the limits for exposures to pulsed sources, and to consider the potential of flash exposure in low ambient light levels, a pupil of 7 mm in diameter was applied. However, for longer exposure durations the closure of the pupil reduces the retinal irradiance as shown in Figure 4

(Stamper; Lund; Molchany; Stuck 2002) and therefore reduces the risk of injury. The pupillary closure decreases the retinal illumination level faster than the damage threshold expressed as retinal irradiance is reduced for exposure durations longer than 0.25 s. Eye movements and blood flow (Ness; Zwick; Stuck; Lund; Sliney 1999) also reduces the risk of thermal injury.

12.1.2 Revision of the retinal thermal hazard function

The study by (Lund; Stuck; Edsall 2006) corrected the retinal thermal hazard function $R(\lambda)$. When $R(\lambda)$ was first derived more than two decades ago there was a controversy as to the possible synergistic effects between photochemical and thermal retinal damage mechanisms at wavelengths less than 500 nm (blue light). There were two controversial threshold data points for the wavelength of 441.6 nm published by (Ham; Mueller; Sliney 1976, Ham Jr 1989) for blue wavelengths and exposure durations of 1 s and 16 s. It was expected at that time that further research would soon be conducted to determine whether these thresholds were in fact correct, or as existing theory would predict - were apparently one order of magnitude too low. Lund et al (Lund; Stuck; Edsall 2006) showed conclusively that the originally published thresholds were indeed one order-of-magnitude too low. This discrepancy was attributed to an error in the dose calculation performed at that time. The more recent study was far more comprehensive than the initial study that had given rise to the conservative adjustment of the $R(\lambda)$ function to provide values greater than 1.0. It had always been assumed that these values were likely to be a great over statement of the risk and for that reason the $R(\lambda)$ function was not normalized at the maximum value were the $R(\lambda)$ values were at 10.0 (at 435 and 440 nm). After a review of the original work and the recent study, ICNIRP concluded that the $R(\lambda)$ function values above 1.0 were indeed unjustified. The adjustment to the values for $R(\lambda)$ included setting $R(\lambda) = 1.0$ for wavelengths from 445 nm to 495 nm and multiplying all values of $R(\lambda)$ from 385 nm to 440 nm by 0.10. The revised values for the spectral weighting functions are provided in Table 2. No changes to the Aphakic or Blue-Light Hazard Functions (ICNIRP 1997) were required.

12.2 Retinal photochemical hazard to the aphakic and infant eye

At one time, patients treated surgically for cataract did not receive intra-ocular lens (IOL) implants, although such patients are rare today. However, during the surgical removal of a cataract, and before the IOL has been implanted, the patient is exposed to near-ultraviolet radiant energy of approximately 300–400 nm from surgical operating lights (Michael; Wegener 2004). Very occasionally, an individual may be born without a crystalline lens. It is under these special conditions that the aphakic photochemical retinal hazard exists; this is a more serious type of blue-light retinal hazard. In case of aphakia, additional ocular UVR protection should be used under UVR exposure conditions. Moreover, UVR transmittance of the crystalline lens is much higher in infants under the age of 2 years than in older children and adults. For this reason eye protection should be considered close to water or in snow.

This potential retinal hazard is evaluated by spectrally weighting the radiance against the blue-light hazard function, altered for wavelengths less than 440 nm for the aphakic eye; this altered $B(\lambda)$ function is given the symbol $A(\lambda)$. The approach is to substitute $A(\lambda)$ for $B(\lambda)$ in Eq. 6 to Eq. 11.

For $t \leq 10\,000$ s, the effective aphakic hazard radiance, L_{Aphake} ,can be calculated from the spectral radiance, L_λ, with the aphacic hazard function, $A(\lambda)$ (Figure 5, Table 2) as a weight (A 1).

$$L_{Aphake} = \sum_{300}^{700} L_\lambda \cdot A(\lambda) \cdot \Delta\lambda \leq 1.0\ MJ \cdot m^{-2} \cdot sr^{-1}\ effective \qquad A\ 1$$

12.3 Comparison with exposure limits for laser radiation

The biological effects induced by all types of optical radiation should be similar for any given exposure site, area, and duration of exposure in the same spectral region. High power laser pulses may induce two-photon absorption which can never occur with incoherent radiation. For a given broadband source it is necessary to consider several possible types of injury (with different wavelength, pulse duration and spot size dependencies), while for laser radiation for a given single wavelength, exposure geometry and exposure duration, the most restrictive injury type is defined.

The degree of quantitative uncertainty in relating biological thresholds, derived from broad-band and narrow-band sources to laser exposure, has frequently necessitated the use of additional reduction factors in deriving the exposure limits for lasers that are unnecessary for broad-band optical sources (ICNIRP 2000).

To the extent possible, both sets of exposure limits closely parallel those for lasers. In the UV wavelength range and for retinal hazards, the two sets of exposure limits are essentially equivalent. However, for the convenience of the application of the guidelines, the retinal limits are expressed in different units for the two sets of limits, since the default condition for laser radiation is a small source, while for non-laser sources, only extended sources can constitute a retinal hazard. For lasers, it is also necessary to define limits for short pulses.

During the preparation of this document, ICNIRP was composed of the following members: P. Vecchia, Chairman, Italy; M. Hietanen, Vice-Chairperson, Finland (until 2008); R. Matthes, Vice-Chairman, Germany; A. Ahlbom, Sweden (until 2008); E. Breitbart, Germany (until 2008); M. Feychting, Sweden; A. Green, Australia; F.R. de Gruijl, The Netherlands (until 2008); K. Jokela, Finland; J.C. Lin, United States of America; A.P. Peralta, The Philippines; K. Schulmeister, Austria; P. Söderberg, Sweden; B.E. Stuck, United States of America; A.J. Swerdlow, United Kingdom; M. Taki, Japan (until 2008); R. Saunders, United Kingdom; B. Veyret, France.
The Task Group, which prepared the draft guidelines was composed of the following

members: P. Söderberg, Chairman, Sweden; B. Stuck, (Chairman until 2008), USA; D. Sliney (until 2008); K. Schulmeister, Austria; B. Lund, USA; R. Thomas, USA. ICNIRP also gratefully acknowledges the useful comments received from D.J. Lund, USA and R. Matthes, Germany, in the drafting phase.

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13. DEFINITION OF SYMBOLS

Table 4 Definition of symbols

Symbol	Quantity	Units	Comment
A(λ)			Aphakic hazard function
B(λ)			Blue-light hazard function
D	Radiance dose/Time integrated radiance	J m^{-2} sr^{-1}	
D	Radiance dose/ time integrated radiance	J sr^{-1} m^{-2}	Time integrated radiance
D_R	The effective retinal thermal damage radiance dose	J sr^{-1} m^{-2}	Time integrated radiance dose spectrally weighted for retinal thermal damage
D_B	The effective retinal blue light damage radiance dose	J sr^{-1} m^{-2}	Time integrated radiance dose spectrally weighted for retinal blue light damage
d_e	Pupil diameter	mm	
E	Irradiance or illuminace (incident to a surface)		(fr. eclairage) Used related to: Physical response, index e (fr. energique) Visual response, index v (fr. visuelle)
E_B	Blue light irradiance	W m^{-2} (eff.)	Spectrally weighted quantity
E_e	Irradiance/ Dose rate	W m^{-2}	Index used only when needed for clarity
E_v	Illuminance	lm m^{-2}	Index used only when needed for clarity
E_r	Retinal irradiance	W m^{-2}	
E_λ	Spectral irradiance	W m^{-2}·nm^{-1}	
F	Focal length	m, but suffix depends on formula	
H	Exposure	J m^{-2}	Used related to Physical response, index e (fr. energique) Visual response, index v (fr. visuelle)
H_e	Radiant exposure/ Radiant dose	J m^{-2}	Index used only when needed for clarity
H_v	Light exposure	lm s m^{-2}	Index used only when needed for clarity
IRR			Infrared radiation
IR-A			Infrared radiation type A
IR-B			Infrared radiation type B
IR-C			Infrared radiation type C
L	Brightness (emission from a source)		Used related to Physical response, index e (fr. energique) Visual response, index v (fr. visuelle)
L_{Aphake}	Aphakic hazard radiance	W sr^{-1} m^{-2} (eff.)	Spectrally weighted quantity
L_{IR}	Near infrared radiance	W sr^{-1} m^{-2}	
L_e	Radiance	W sr^{-1} m^{-2}	Index used only when needed for clarity
L_v	Luminance	lm sr^{-1} m^{-2} or cd m^{-2}	Index used only when needed for clarity
L_R	Radiance	W·sr^{-1}·m^{-2} (eff.)	Radiance spectrally weighted for thermal injury
L_B	Blue light hazard radiance		Radiance spectrally weighted for blue light damage
L'	Spatially averaged radiance		
L_s	Source radiance	W sr^{-1} m^{-2}	
L_λ	Spectral radiance	W sr^{-1} m^{-2} nm^{-1}	
Q	Energy	J	

$R(\lambda)$			Retinal thermal hazard function
T	Time	S	
t_{max}	Maximum exposure duration	S	
UVR			Ultraviolet radiation
α	Angular subtense (of a source)	Mrad	
α_{min}	Minimal source angular subtense	Mrad	
α_{max}	Maximal angular subtense of an intermediate source	Mrad	
γ	Field of view	Mrad	
γ_{meas}	Measurement field of view	Rad	
γ_{th}	Field of view for assessing thermal hazards	Mrad	
γ_{ph}	Field of view for assessing photochemical hazards	Mrad	
λ	Wavelength	nm	
τ	Transmittance	Rel.	
Φ	Power	W	
Ω	Solid angle	Sr	

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