GUIDELINES ON LIMITS OF EXPOSURE TO BROAD-BAND INCOHERENT OPTICAL RADIATION (0.38 TO 3 μM)

International Commission on Non-Ionizing Radiation Protection*

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INTRODUCTION

ELECTROMAGNETIC RADIATION in the wavelength range between approximately 100 nm and 1 mm is widely termed "optical radiation." Optical radiation of wavelength 100–400 nm is termed ultraviolet (UV) radiation and that of wavelength 380–780 nm visible radiation (or light). Radiation in the wavelength range 780 nm to 1 mm is known as infrared (IR) radiation. The infrared region is often subdivided into IRA (780–1,400 nm), IRB (1,400–3,000 nm), and IRC (3,000 nm—1 mm). These spectral bands, defined by the International Commission on Illumination (CIE 1987), can be useful as "short hand" in discussions of the photobiological effects of optical radiation although the predominant effects have less sharply defined spectral limits. Indeed, this is emphasized by the CIE's intentional overlap of UV A and light between 380 and 400 nm.

In general, most high-intensity broad-band sources (e.g., arc and incandescent sources) produce negligible levels of IRC compared with the emissions at shorter optical wavelengths; IRC radiation can thus be largely ignored when a risk assessment is made. These guidelines contain no recommended exposure limits for IRC radiation. Only lasers pose potential hazards in this spectral region. Normally, therefore, guidelines for broad-band optical exposure limits would be assessed only in the IRA, IRB, and visible spectral bands (with extension into the UV in certain cases).

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. In certain unusual situations, however, potentially hazardous levels are accessible, and excessive light and infrared radiation are typically filtered or baffled to reduce discomfort. Where sufficient 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 will also produce an aversion response. Nevertheless, certain exposures remain potentially hazardous. Examples include those that may result from arc welding; use of some arc lamps in research laboratories, very high intensity flash lamps in photography, and infrared lamps for surveillance and heating; a number of medical diagnostic applications; and even printing and photocopying.

Many intense optical sources also produce significant amounts of ultraviolet radiation, which may be hazardous to the eye and skin; this hazard should be separately assessed, using UV guidelines (Duchêne et al. 1991). It should be noted, however, that the UV guidelines do not take account of photoretinitis action spectra: the photoretinitis risk 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 generally have limited intensities and, therefore, seldom pose an actual hazard. Light-emitting diodes (LEDs) emit relatively narrow-band optical radiation, which may not evoke a strong aversion response. Currently, the most intense LEDs emit in the wavelength range between 670 nm and 900 nm (red light and near-infrared radiation); in the future, more intense sources are likely to emit radiation at shorter wavelengths.

The optical properties of lasers are special and differ significantly from those of conventional, broad-band optical sources, and so the exposure limits for broad-band optical sources necessarily differ from those applicable to lasers. In addition, laser guidelines incorporate assumptions of exposure that may not apply to conventional optical sources (IEC 1993; ICNIRP 1996). 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. 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 may apply to different

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* At the 8th International Congress of the International Radiation Protection Association (Montreal, 18–22 May, 1992), the IRPA chartered an independent scientific organization, the International Commission on Non-Ionizing Radiation Protection (ICNIRP), as a continuation of the former IRPA/International Non-Ionizing Radiation Committee (IRPA/INIRC). The functions of the Commission are to investigate hazards that may result from the different forms of non-ionizing radiation (NIR), draft international guidelines on exposure limits, and to deal with all aspects of NIR protection.

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ocular structures and the biological effects are not additive.

Adverse health effects of exposure to intense light sources are theoretically possible across the entire optical spectrum, but the risk of retinal injury due to radiation in the visible and near-infrared is of particular concern. Exposure limits vary enormously across the optical spectrum because of variations in biological effects and the different structures of the eye that are potentially at risk.

In 1982, under the joint sponsorship of the United Nations Environment Programme, the World Health Organization, and the International Radiation Protection Association, a review was published of the reported biological effects of exposure to optical radiation from lasers and other sources (UNEP/WHO/IRPA 1982). Although further biological data have been published since that time (Suess and Benwell-Morison 1989; Duchêne et al. 1991; ACGIH 1995), the basic findings and conclusions of that review are still current and served as the scientific rationale for the development of these guidelines.

No guidelines for exposure to visible and infrared radiation have been proposed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), but related guidelines on limits of exposure to UV and laser radiation have been published and revised (Duchêne et al. 1991; ICNIRP 1996). Because there are differences between broad-band incoherent optical sources and monochromatic laser sources, and between the worst-case conditions for the two, and because a number of simplifying assumptions were used to derive laser exposure limits, it is necessary to recommend different exposure limits that are more realistic for incoherent sources.

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

The biological data on which exposure limits were based were developed using conventional optical sources with emissions over a broad band of wavelengths; additional data from some laser studies permitted the refinement of action spectra. These broad-band optical exposure limits do not include the additional safety factors that are required for highly monochromatic laser wavelengths (see ICNIRP 1996). Exposure limits for broad-band optical sources and for lasers have similar time- and spot size-dependence; however, a more precise wavelength-dependence is applied in developing broad-band exposure limits.

Studies of the biological effects of lasers were consulted to provide a better understanding of the mechanisms of interactions within certain wavelength regions. Results of physiological studies of involuntary eye movements, behavioral studies of voluntary eye movements, and theoretical studies of heat flow using mathematical models were also employed in developing the exposure limits.

During the preparation of these guidelines, the composition of the International Commission on Non-Ionizing Radiation Protection was as follows: A. Ahlbom (Sweden); U. Bergqvist (Sweden); J. H. Bernhardt, Chairman since May 1996 (Germany); J. P. Césarini (France); L. A. Court (France); M. Grandolfo, Vice-Chairman through April 1996 (Italy); M. Hietanen, since May 1996 (Finland); A. F. McKinlay, Vice-Chairman since May 1996 (UK); M. H. Repacholi, Chairman through April 1996 (Australia); D. H. Sliney (USA); J. A. J. Stolwijk (USA); M. L. Swicord (USA); L. D. Szabo (Hungary); M. Taki (Japan); T. S. Tenforde (USA); H. P. Jammet (France) (Emeritus Member), deceased; and R. Matthes, Scientific Secretary (Germany).[†]

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

PURPOSE AND SCOPE

The purpose of these guidelines is to establish the basic principles of protection against visible and infrared radiation emitted by broad-band, conventional, non-laser sources (including LEDs). They 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 ns and 8 h (30 ks) and apply to radiation at wavelengths from approximately 380 nm to 3,000 nm (3 μm). However, the action spectrum for photoretinitis extends to 300 nm in the UV range and should be applied for the evaluation of broad-band sources which may also emit UV. Radiation in this region normally contributes only a tiny fraction of the retinal hazard from most light sources, even in the case of aphakic individuals (those who have lost the crystalline lens, which would normally block UV radiation) and of children under the age of 2 y. Guidelines for incoherent infrared radiation of wavelength greater than 3 μm are unnecessary because non-laser sources do not emit significantly in this region.

The guidelines apply to all exposure, both acute and chronic, to optical radiation emitted by the sun and by artificial non-laser light sources, but exclude deliberate exposure carried out as an integral part of medical

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treatment. In general, however, diagnostic procedures should not exceed the exposure limits (although limits may need to be differently expressed because of altered pupil size or altered sensitivity during anaesthesia). While safety factors are built into the exposure limits, exposure above the adjusted guidelines should be the subject of a risk/benefit analysis.

QUANTITIES AND UNITS

Two sets of quantities and units, *radiometric* and *photometric*, are useful in defining visible radiation exposure (CIE 1987; IRPA/INIRC 1985). Radiometric quantities include *radiance* (expressed in W m^{-2} sr^{-1} and used to describe the "brightness" of a source) and *irradiance* (expressed in W m^{-2} and used to describe the irradiation of a surface). Photometric quantities such as *luminance* (brightness, in cd m^{-2}, as perceived by a human "standard observer") and *illuminance* (the "light" incident on a surface, expressed in lm m^{-2} or lux) indicate light levels spectrally weighted by the standard photometric visibility curve V(λ) for daylight (photopic vision) which peaks at 555 nm for the human eye. There is a second visual response for night (scotopic) vision, which peaks at 505 nm: this is the rod response. Radiance and luminance are particularly valuable because they describe the source and do not vary with the distance of the observer from the source. To quantify a photochemical effect it is not sufficient to specify the photon flux (the number of photons per square meter) or the irradiance, since the efficiency of the effect is highly dependent on wavelength. Generally, shorter-wavelength, higher-energy photons are more biologically effective.

Photometric quantities are defined by an action spectrum for vision—a photochemically initiated process—and certain of them may have little value in describing adverse retinal effects other than on temporary disturbances of vision or in research relating to neuroendocrine effects mediated by the visual system. Unfortunately, since the spectral distributions of different light sources vary widely, there is no simple conversion factor between photometric (either photopic or scotopic) and radiometric quantities. This conversion (the *luminous efficacy of radiation*) may vary from 15 to 50 lm W^{-1} for an incandescent source to about 100 lm W^{-1} for the sun or a xenon arc, and to perhaps 250 to 300 lm W^{-1} for a fluorescent lamp source (Sliney and Wolbarsht 1980).

Exposure limits for optical radiation are expressed using spectral weighting functions with certain radiometric quantities. *Irradiance* (*E*), expressed in W m^{-2}, and *radiant exposure* (*H*), expressed in J m^{-2}, are used in describing the concepts of dose-rate and dose from "point" (or "small") sources—sources that subtend a very small visual angle. *Radiance* (*L*), expressed in W m^{-2} sr^{-1}, and *time-integrated radiance* (L_p), expressed in J m^{-2} sr^{-1}, are used to describe the "brightness" of an extended source that gives rise to an image on the retina. In addition, spectroradiometric quantities such as *spectral irradiance* (E_λ), expressed in W m^{-2} nm^{-1}, must be employed to spectrally weight the source spectrum with the applicable action spectrum, which describes the relative effectiveness of optical radiation of different wavelengths in producing a photochemical effect.

RATIONALE FOR THE EXPOSURE LIMITS

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 as shown in Fig. 1. Since the skin is normally less sensitive to injury from visible and infrared radiation, the exposure guidelines calculated for the eye will be more restrictive than those for 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 1982; Suess and Benwell-Morison 1989; Duchêne et al. 1991; Health Council of the Netherlands 1993; ACGIH 1995).

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 outdoor environmental exposures to visible radiation are not normally hazardous to the eye except in environments producing reflections from surfaces such as snow and sand.

BIOLOGICAL EFFECTS

Mechanisms of interaction with biological tissue

The eye is adapted to protect itself against optical radiation from the natural environment, and humans use appropriate additional protective devices. By limiting the duration of exposure to less than 0.25 s, the aversion

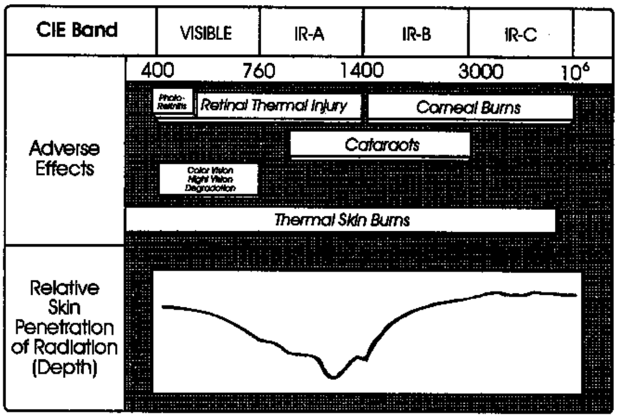

Fig. 1. Adverse biological effects vary with the spectral band. The effects may overlap and must therefore each be evaluated independently. Action spectra exist for each effect. The relative penetration is provided only as a general indication, hence a scale of depth is not provided.

response normally protects the eye against injury from viewing bright light sources such as the sun, arc lamps, and welding arcs. Squinting provides further protection.

Tissue interactions in the spectral range addressed in these guidelines are either thermally or photochemically initiated. At least five separate types of damage to the eye and skin may be caused by visible and infrared optical sources (see Fig. 1):

a. thermal injury of the retina (380–1400 nm);
b. "blue-light" photochemical injury of the retina (principally 380–550 nm; 300–550 nm for the aphakic eye) (Ham et al. 1976; Ham 1989);
c. near-infrared thermal injury of the crystalline lens (approximately 800–3,000 nm);
d. thermal injury (burns) of the skin (approximately 380 nm to 1 mm) and cornea (approximately 1,400 nm to 1 mm); and
e. photosensitized injury of the skin, which is generally far more typical of UV wavelengths (less than 380 nm), although such photosensitized reactions can extend to approximately 700 nm, possibly as a side-effect of certain medications (Fitzpatrick et al. 1974; Magnus 1976; Diffey 1982).

Skin cancer caused by optical radiation sources in the absence of ultraviolet radiation is not considered to be a significant risk (IARC 1992; UNEP/WHO/IRPA 1994).

Characteristics of photochemical interaction mechanisms. The threshold dose for photochemical injury is the product of the dose-rate and the exposure duration. It is subject to the principle of *reciprocity* (the Bunsen-Roscoe Law of Photobiology); thus, for example, blue-light retinal injury (photoretinitis) can result from viewing either an extremely bright light for a short time or a less bright light for longer. Reciprocity helps to distinguish these effects from thermal injuries (see below). For photochemical injury of the retina, the action spectrum peaks at approximately 440 nm for the eye with an intact crystalline lens (i.e., the phakic eye).

Characteristics of thermal interaction mechanisms. Unlike photochemical injury, thermal 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 as shown in Fig. 2 (Priebe and Welch 1978; Allen and Polhamus 1989). 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. This more rapid cooling of small images also limits the duration of elevated temperature after the cessation of optical exposure, therefore influencing the critically important time-temperature history of the exposed tissue. Thus there is no single critical temperature for a given exposure duration: the spot size must be specified for defining ocular or skin exposures.

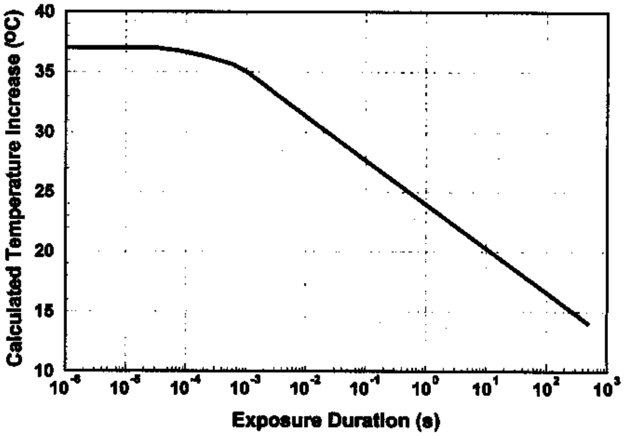

Fig. 2. The calculated peak temperature rise (at the image radius) necessary to result in retinal thermal injury in a 50 μm retinal image as a function of duration of light exposure (Priebe and Welch 1978; Allen and Polhamus 1989). Because of longer cooling times for larger images, smaller peak temperatures would be required for significantly larger retinal images, but the general trend will be similar.

Retinal injury

The principal retinal hazard from viewing bright light sources is photoretinitis, e.g., solar retinitis with an accompanying scotoma from staring at the sun. Solar retinitis was once referred to as "eclipse blindness" and associated "retinal burn." In recent years it has become clear that photoretinitis is the result of a photochemical reaction following exposure of the retina to shorter wavelengths in the visible spectrum, i.e., violet and blue light (Ham et al. 1976), and it is now frequently referred to as blue-light retinal injury (Sliney and Wolbarsht 1980). Only the very high radiances of sources such as a xenon-arc flash lamp, a nuclear flash or a laser are capable of producing *thermal* injury of the retina (Byrnes et al. 1956). However, even photoretinitis caused by welding arcs has been mistakenly referred to as resulting from "heat" or "infrared" (Naidoff and Sliney 1974; Brittain 1988; Garcia and Wiegand 1989; Fich et al. 1992).

Laboratory studies suggest that photochemical injury from chronic low-level exposure 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). However, small temperature rises in the retina (of the order of 2–3°C) appear to be synergistic with the photochemical process, so that absorption by melanin over a broad wavelength band will also play a role, albeit secondary. The effect of an increase in body temperature is to lower—by about 20%—the photochemical retinal injury threshold (Ham 1989). This effect becomes negligible, however, if a safety factor of more than 5 is applied to the threshold. Shorter-wavelength visible radiation has also been suggested to accelerate retinal aging (Marshall 1983; Young 1988), although clearly there is more than one action spectrum for photochemical damage from lengthy exposures (more than 2–3 h) (Noell 1980; Sperling 1986; Mainster 1987; Kremers and van Norren 1988; Sliney 1988). In deriving the exposure limits for photoretinitis (Fig. 3), the Commission decided that the acute photoretinitis action spectrum of Ham (1989) was the most appropriate for determining hazards from blue light. Plausible exposure durations for viewing intense light sources are similar to the duration of the aversion response (< 0.20 s) (Gerathewohl and Strughold 1953)—or rather longer in special circumstances of intentional fixation. 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 behavioral reactions such as movement of the head (Fender 1964; Yarbus 1977). The effect of eye movements on time-averaged image area and retinal irradiance is illustrated in Fig. 4.

The mechanisms involved in acute 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. Although there are no clear boundaries between injury mechanisms, certain mechanisms dominate depending on the spectral region and the exposure duration. For short-duration exposures (less than a few seconds), the damage is due to thermal injury at threshold. 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. Photochemical, rather than thermal, effects dominate only in the wavelength region below approximately 600–700 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. Eye movements (at exposure times greater than about 0.1 to 10 s) also create a spot-size dependence for photochemical retinal injury (Fender 1964; Naidoff and Sliney 1974; Yarbus 1977; Sliney 1988, 1989).

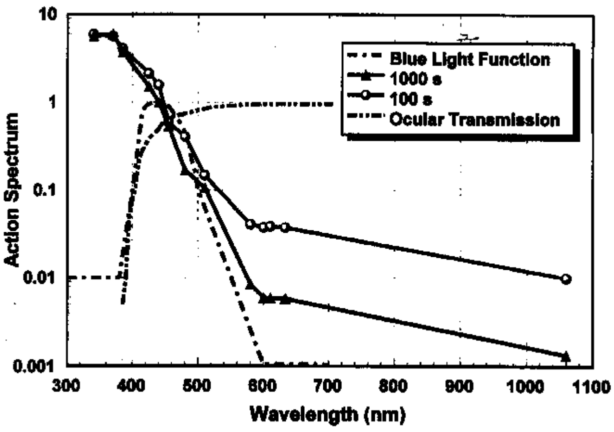

Fig. 3. Action spectra for blue-light photoretinitis for the rhesus monkey without an intact crystalline lens (Ham and Mueller 1989), and the $B(\lambda)$ function when the spectral absorption of the ocular media is taken into account. The recommended standard action spectrum $B(\lambda)$ is shown as a solid line and is the limit for no thermal effect. The two right-most points at 630 and 1,060 nm show the thermal irradiance plateau which, as expected, would differ by a factor of about 10 in radiant exposure when going from exposure durations of 100 s to 1,000 s to achieve a nearly constant retinal irradiance. The actual spectral dependence of retinal thermal hazard from 630 to 1,060 nm is not a straight line, but varies because of spectral changes in the retinal reflectance, absorption of the pigment epithelium, and the absorption of the ocular media.

Skin injury

Photosensitized injury of the skin by visible radiation is possible as a result of the presence of both endogenous and exogenous photosensitizers such as serum bilirubin and phenothiazine. Although this effect is far less likely to be caused by light than by UV radiation, it may occur with the ingestion of certain photosensitizing molecules in food or medicines (Fitzpatrick et al. 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 of the skin is rare from most nonlaser sources and is highly dependent upon the source size and the initial skin temperature (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). 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.

DERIVATION OF EXPOSURE LIMITS

Adverse biological effects of radiation are theoretically possible across the entire optical spectrum, but there is particular concern about the visible and near-infrared regions 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 broad-band optical sources that emit light and infrared radiation must therefore be evaluated against several specific action spectra.

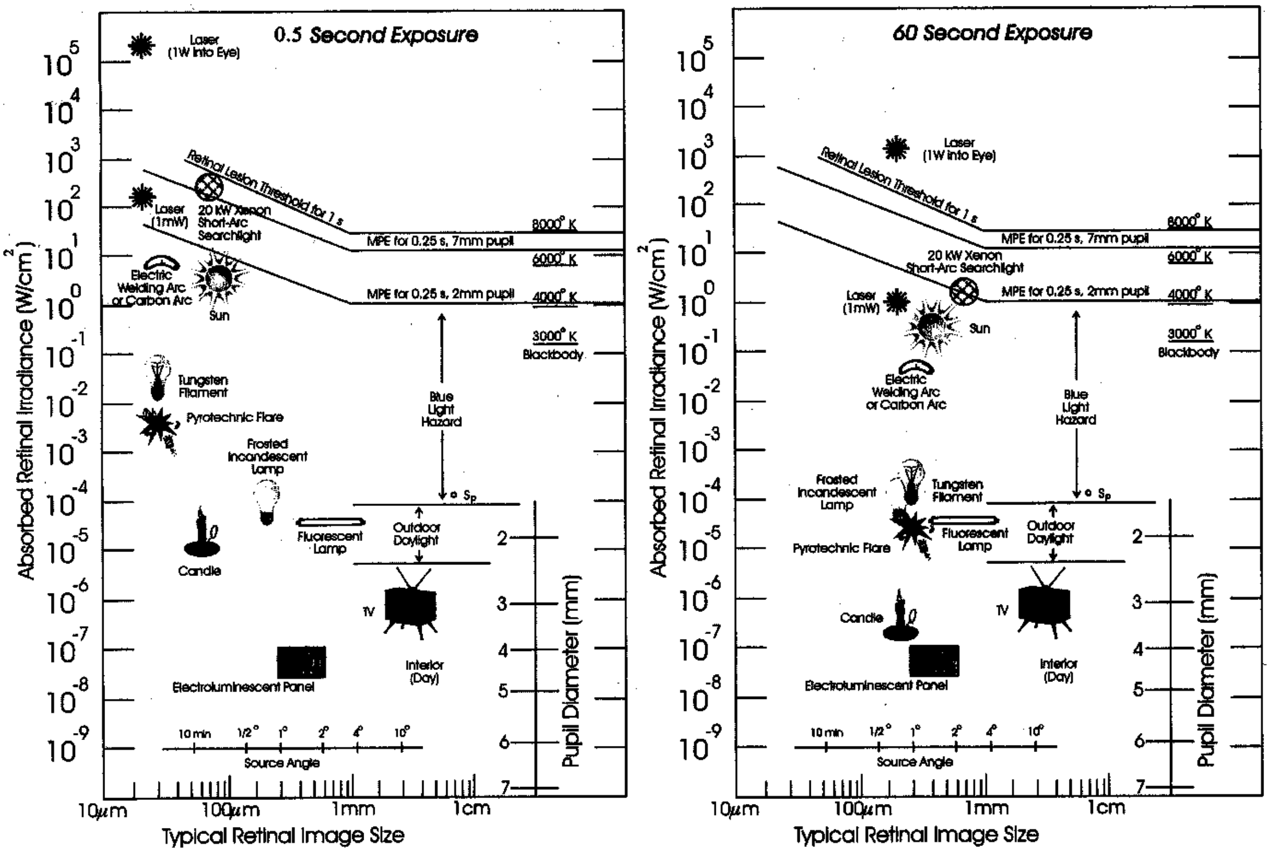

Fig.4. Comparative retinal irradiances of characteristic light sources as a function of image size (left panel) and as an average irradiance resulting from eye movements (right panel) which displace the retinal irradiance downward for very small image sizes (adapted from Sliney and Wolbarsht 1980). In the left panel for an exposure duration of 0.25 s (aversion response), the retinal areas affected by the image are normally the same as the actual optical image size; however, for a 60-s exposure, eye movements spread the optical energy of small images (less than about 200–300 µm) to average the image irradiance as shown in the right panel.

Comparison with exposure limits for laser radiation

The exposure limits for both conventional light sources and lasers (pulsed and continuous) are based on human and animal thresholds for ocular injury. According to current knowledge, and because the expression of fundamental limits for use with lasers may be simplified, the exposure limits and safety factors for the two sources necessarily differ. The use of all laser limits as if they constituted an action spectrum to spectrally weight a broad-band source would result in a very conservative hazard evaluation, since multiple effects from different wavelength bands would be summed together. Because the ocular exposure limits were derived to protect different structures (e.g., cornea, lens, retina), the different biological effects are not additive.

The biological effects induced by incoherent and coherent optical radiation are believed to be similar for any given exposure site, area, and duration of exposure in the same spectral region, but thresholds of injury can differ for very narrow spectral bandwidths. Therefore, laser radiation must be treated as a special case because of the spectral purity and radiant intensities achieved only by lasers. Data for many biological effects are based on broad-band optical sources and are therefore not directly applicable to the highly monochromatic emissions of lasers. 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 safety factors in deriving the exposure limits for lasers that are unnecessary for broad-band optical sources.

To the extent possible, the exposure limits for incoherent sources closely parallel those for lasers as a function of time. Potential photobiological effects of narrow-band radiation had to be considered in deriving the exposure limits for the very narrow spectral bandwidths of lasers; a safety factor of greater magnitude was therefore used for laser exposure limits than for the limits for broad-band light sources. This approach was justified by the results of studies of threshold injury to the retina caused by tunable pulsed and continuous wave lasers from 550 to 1,000 nm (Lund et al. 1988). However, if the

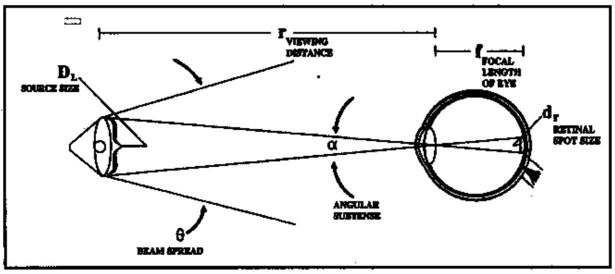

Fig. 5. Geometry of ocular exposure. The angular subtense of the source is the angle α subtended by the actual light source (not the fixture), and the beam spread θ of the source will not normally be the same as the angular subtense of the source.

emission from a broad-band light source is spectrally weighted by the appropriate action spectrum, any narrow-band spectral sensitivity would be insignificant. For example, individual lines in a xenon-arc or metal-halide spectrum contribute only a very small fraction of the total radiated energy. On the other hand, low-pressure gas discharges with few lines in the visible and infrared have relatively low brightness and therefore do not pose a realistic problem.

Another special aspect of laser exposure is that intrabeam viewing results in a minimal retinal image size, and irradiance of the retina far exceeds that of the cornea and lens. In many instances, however, exposure to incoherent light sources produces corneal and lenticular irradiance comparable to, or even exceeding, retinal irradiance (as in Maxwellian-view optics). For this reason, it is critical that corneal/lenticular hazards be evaluated independently from retinal hazards.

In developing exposure limits for broad-band optical sources, action spectra were specified and used to spectrally weight source emissions to derive a "biologically effective radiance or irradiance." This provides the most accurate hazard assessment; exposure limits can then be specified in terms of exposure duration and other relevant parameters so that all sources are evaluated with the same risk criteria. For historical reasons, however, derivation of laser exposure limits was based on some knowledge of the action spectra and on drawing conservative, "simple-to-apply" tables of exposure limits, all set below the thresholds of injury. This was possible because, for any given single wavelength, exposure geometry and exposure duration, the biological threshold data predict one dominant injury mechanism. For broad-band sources, with quite variable spectra, this is not generally the case; at a given exposure duration, one damage mechanism (e.g., thermal) may be dominant for one source while another mechanism (e.g., photochemical) may dominate for a source of different configuration. In addition, there may be more than one effect (e.g., photoretinitis *and* thermal damage to the lens). Any attempt to employ all laser limits as if they were one action spectrum over a full-spectrum source would result in a needlessly conservative evaluation, since all hazards—from the ultraviolet to the infrared—would be grouped together. Thus, a calculation exceeding this single-action-spectrum limit would give no indication of the particular photobiological hazard for which protection was required. Because photochemical injury follows the "reciprocity rule," the exposure limit can be expressed simply as a radiant exposure; duration of exposure need not be specified. Thermal mechanisms, however, depend also on the duration of exposure and exposure area, because of heat flow away from the irradiated site.

Retinal image size and source size

For the small retinal images typical of viewing intense light sources, the image dimension, d_r, is directly related to the source dimension, D_L, by

$$d_r = D_L(f/r), \tag{1}$$

where f is the effective focal length of the eye in air (i.e., 17 mm) and r is the viewing distance from the light source (Fig. 4) (Sliney and Wolbarsht 1980). Note: The mean light-source dimension is the diameter of a circular source, but for a rectangular source it is the arithmetic mean of the shortest and longest dimensions.

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 (eqn 2). In physiological optics it is necessary to distinguish between a "point source" and an "extended source." As a source is viewed at ever-increasing distance, it begins to behave as a point source and eqn (1) becomes invalid for image dimensions less than approximately 25–50 μm (Sliney and Wolbarsht 1980). The exposure limits for extended sources and small (or "point") sources are expressed in different units. 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 (α_{meas}), is defined, over which the measured radiance is averaged, all of the retinal hazard limits can be expressed as radiance. This measured radiance can then be reduced to an equivalent irradiance by multiplying by the solid angle S corresponding to α_{meas} {i.e., by $[(\pi/4)\alpha_{meas}{}^2]$}. The measurement conditions are discussed below.

Calculating retinal exposure

Retinal irradiance (exposure rate) is directly related to source radiance (brightness). It is *not* readily related to corneal irradiance (Sliney and Wolbarsht 1980). Eqn (2) gives the general relation, where E_r is the retinal irradiance (W cm^{-2}), L_s is the source radiance (W cm^{-2} sr^{-1}), f is the effective focal length of the eye (cm), d_e is the pupil diameter (cm), and τ is the transmittance of the ocular media:

$$E_r = \pi L_s \cdot \tau \cdot d_e^2/4f^2. \tag{2}$$

This formula is derived by considering the equal angular subtense of the source and the retinal image at the nodal point of the eye (near the posterior pole of the crystalline lens) as derived from eqn (1). The detailed derivation of this formula is given elsewhere (Sliney and Wolbarsht 1980). For the visible spectrum, transmittance τ in the ocular media for younger people (and most animals) is as high as 0.9 (i.e., 90%) (Geeraets and Berry 1968). Using the effective focal length f of the adult human eye (Gulstrand eye, f = 17 mm):

$$E_r = 2700 \cdot L_s \cdot \tau \cdot d_e^2. \tag{3}$$

Eqn (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 eqn (2) is valid if the contribution of scattered light (which falls over the entire retina) is added. Recently, Barker and Brainard (1997) have shown that more than 1% of the energy incident on the cornea may reach the retina at wavelengths less than 380 nm in young children.

For retinal thermal injury, the thresholds vary with retinal image size because of radial heat flow, which is far more efficient for a small image. Mathematical models and experimentally determined thresholds for retinal thermal injury show that threshold irradiance varies more or less inversely with the image diameter d_r for values of d_r from approximately 20–25 μm to approximately 2,000 μm (Allen and Polhamus 1979; Sliney and Wolbarsht 1980; Courant et al. 1989). For image diameters greater than 2 mm there is little or no spot-size variation, and a constant radiance applies. A measurement acceptance angle, $\alpha_{\max}$, of 0.1 radian can therefore be specified for evaluating very large sources for thermal retinal injury.

The effect of eye movements and heat flow

The distribution in retinal tissue of the radiant energy that may lead to injury depends not only on the retinal irradiance but also—very strongly—on radial heat flow, which cools the image and thereby limits thermal injury, as well as on continuous eye movements. These factors are of major significance in the derivation of the exposure guidelines. Thus, in considering retinal injury mechanisms, exact geometric definitions are not able to distinguish between a "minimal retinal image" and larger images, or to specify a single "minimal source size." The exposure limits for extended sources apply to sources that subtend a visual angle at the eye greater than "alpha-minimum" ($\alpha_{\min}$), which varies with exposure duration. This angle is 1.7 mrad for very short pulse durations and 11 mrad for exposures of 10–100 s, when involuntary eye movements dominate. For very long exposures of 1,000 s or more, when task-determined eye movements dominate, the angle is more than 100 mrad. These average angular fields of view correspond to retinal image dimensions of 30 μm, 200 μm, and 1.7 mm, respectively, at the retina. The angle α used in evaluating the risk of thermal injury is the visual angle at the eye equal to the quotient of the source diameter and the viewing distance. For a non-circular source, α is the arithmetic mean of the shortest and longest source dimensions divided by the viewing distance (Freund et al. 1996). The angular subtense of a source (i.e. the apparent visual angle) 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) it is equivalent (see Fig. 5).

Exposure of the anterior structures of the eye

Any calculation of potential retinal thermal hazards normally includes a consideration of the contributions of IRA (780–1,400 nm) and IRB (1.4–3.0 μm). In contrast to blue light, IRA is very ineffective in producing retinal injuries (Ham et al. 1976, 1982). Data on which to base exposure limits for chronic exposure of the anterior portion of the eye to infrared radiation are very limited. Sliney and Freasier (1973) stated that the average corneal exposure from infrared radiation in sunlight was of the order of 1 mW cm^{-2}. Glass and steel workers exposed in hot environments to infrared irradiances of the order of 80–400 mW cm^{-2} daily for 10–15 y have reportedly developed lenticular opacities (Sliney and Wolbarsht 1980; Lydahl 1984). Calculation of corneal and lenticular exposure dose is significantly affected by both the relative position of the light source and the degree of lid closure.

As previously noted, rapidly changing photochemical action spectra are characteristic of ultraviolet and short-wavelength light exposure, and spectral data are therefore particularly important. However, because the infrared effects are thought to be largely thermal, chronic infrared exposures of the cornea and lens are not believed to involve rapid changes in spectral sensitivity (Barthelmess and Vorneff 1959; Sliney 1986). Radiant energy absorbed in the cornea, aqueous humor, and lens is transported by conduction, and some heating will occur in the lens regardless of the optical penetration depth. Penetration depth strongly varies in the IRA and IRB spectral bands, but these variations—between 1.2 and 3 μm—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). For each degree that ambient temperature falls below 37°C, an added radiant exposure of at least 0.6 mW cm^{-2} would be required to maintain the temperature of the lens (Stolwijk and Hardy 1977).

Infrared exposure

Pitts and Cullen (1981) showed that the threshold exposures for lenticular changes caused by IRA were of the order of 50 MJ m^{-2} (5 kJ cm^{-2}). Threshold damage irradiances were at least 40 kW m^{-2} (4 W cm^{-2}). Wolbarsht (1978, 1992) showed somewhat similar levels using an Nd:YAG laser operating at 1,064 nm, and Scott (1988a, 1988b) showed that the calculated temperature rise was several degrees. Although Vos and 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, and that this level would be acceptable (as with collimated laser beams), such an irradiance over the entire head or much of the body from an incoherent source would not be acceptable for extended periods. The Commission therefore recommends that, for very warm environments (>35°C), the ocular irradiance should not exceed 100 W m^{-2} for lengthy exposures; however, higher irradiances could be safely sustained for shorter periods. Higher irradiances are permitted in cold environments provided that the lenticular temperature is maintained below 37°C. For radiant warming in outdoor environments in winter, irradiances of the order of 300 W m^{-2} are routinely used.

A second criterion is required to protect the retina against thermal injury while viewing specialized infrared illuminators with visible radiation removed by filters—which results in loss of the aversion response. This criterion is based largely on the studies of Ham et al. (1973), who demonstrated the absence of photochemical effects in the infrared spectral bands.

Synergistic effects

The synergism between thermal and photochemical effects in the lens and retina has been studied in a number of experiments. Thermal enhancement of photochemical reactions has been experimentally demonstrated (Pitts and Cullen 1981; Ham 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 margin of safety.

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; otherwise, it is limited by the natural reflex response to high temperature. Hence the Commission provides guidance only for exposures lasting less than 10 s based upon an irradiance averaged over an area at least 10 mm in diameter. 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 1995).

Previous guidelines

A number of national and international groups have recommended limits for occupational or public exposure to optical radiation, particularly ultraviolet. Only two groups have recommended exposure limits for visible radiation—the Health Council of the Netherlands (1993) and the American Conference of Governmental Industrial Hygienists (ACGIH 1995). The Commission took these limits into consideration, but introduced some modifications to their expression and to the values of some of the weighting functions to account for the increased risk from the small fraction of near-ultraviolet radiation that reaches the retina (Zuclich and Conolly 1976; Yanuzzi et al. 1987; Barker and Brainard 1997). The blue-light hazard function, $B(\lambda)$, for example, was extended into this spectral region. The action spectrum, $A(\lambda)$, of increased retinal sensitivity of aphakic individuals (now rare) was also addressed and is dealt with in the Appendix. Because of previous confusion concerned with the determination of realistic viewing conditions and exposure conditions, the Commission has specified measurement fields of view that take into account knowledge of eye movements, lid opening, and visual function.

EXPOSURE LIMITS

Note. Although the Commission concurs generally with SI practice, which avoids the use of the centimeter, the guidelines are expressed in both SI and the older units. Almost all previous guidelines, the WHO Criteria Document, and many biological data express levels in the older units. The two systems of units are used here to avoid potential errors in conversions and comparisons.

The limits for both public and occupational exposure to visible and infrared radiation incident on the skin or eye where irradiances and exposure duration are known or controlled are provided below. Correct application of the exposure limits requires a knowledge of the spectral radiance (L_λ) or spectral irradiance (E_λ) and of source size measured at the position(s) of the eyes. For a white-light source, such detailed spectral data are generally required only if the luminance exceeds 10^4 cd m^{-2} (i.e., 1 cd cm^{-2}). This rule-of-thumb is used to exclude most simple light sources, which do not exceed the exposure limits. It would also be applicable to unfiltered incandescent, fluorescent, or arc sources, which would not exceed the exposure limits for retinal injury provided that the luminance did not exceed about 10^4 cd m^{-2}. Exposure limits are provided for viewing durations in excess of 0.25 s, even though the aversion response to bright light would normally preclude viewing bright visible sources for longer. Thus, when a significant level of visible radiation is emitted, a continuous source should be evaluated only for an aversion response time of 0.25 s or for a maximum of 10 s for normal viewing conditions. In the derivation of the guidelines for retinal exposure, two pupil diameters were assumed: 7mm under dark-adaption and approximately 3 mm for bright light. Two limits are applied to protect against retinal thermal injury: One for general case of broad-band sources which are visible, and a second for infrared sources without a strong visual stimulus. The latter contains an underlying assumption of a 7 mm pupil, the former an underlying assumption of a 7 mm pupil up to approximately 0.5 s, and then with pupillary constriction to about 3 mm. Since the formulation of the general limit does not change at 0.5 s, this adds an additional safty margin between 0.5 s and 10 s, where there is a potential thermal enhancement of photo chemical hazard. If there is concern about longer exposures resulting from determined visual effort or from loss of the aversion response because of reduced visual sensitivity or surgical anaesthesia, the exposure limits for longer durations may be applicable.

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 usually be assumed to represent the worst-case exposure situation. For small sources, such as an optical fibre, the closest distance at which the human eye can sharply focus is about 100–200 mm; 100 mm is an exceptionally small value for the near-point of accommodation and really applies only to small children and to extremely myopic individuals. 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; 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.

The exposure limits are as follows:

Retinal thermal hazards (380–1,400 nm)

Protection of the human retina from thermal injury requires the use of a spectral weighting function, $R(\lambda)$. The exposure limit for hazardous radiance is termed L_{HAZ} and is a function of the angular subtense α (in radians) of the source (the mean light-source dimension D_L divided by the viewing distance r) and the exposure duration t (in seconds) for the condition 10 μs $\leq t \leq$ 10 s:

$$L_{\mathrm{HAZ}} = 50/(\alpha \cdot t^{0.25})(\text{in kW m}^{-2}\text{ sr}^{-1}) \qquad (4)$$

or

$$L_{\mathrm{HAZ}} = 5/(\alpha \cdot t^{0.25})(\text{in W cm}^{-2}\text{ sr}^{-1}).$$

Note: The mean light source dimension is the diameter of a circular source, but for an oblong source it is the arithmetic mean of the shortest and longest dimension. The angular subtense α has a maximum value of 0.1 radian; for any source with a greater angular subtense, α is set at 0.1 radian in eqn (4). The minimum value of the angular subtense is 1.7 mrad when applying the retinal thermal limits. All measurements of radiance should be sufficient to average over 1.7 mrad; hence, for minimal sources, this value of $\alpha_{\min}$ = 1.7 mrad.

The spectral radiance L_λ of the source is weighted against the retinal thermal hazard function $R(\lambda)$ and the resulting effective radiance must not exceed L_{HAZ}:

$$\sum_{380}^{1,400} L_\lambda \cdot R(\lambda) \cdot \Delta\lambda < L_{\mathrm{HAZ}}. \qquad (5)$$

For $t <$ 10 μs the time-integrated radiance should not exceed L_{HAZ} for 10 μs. Since the retinal thermal hazard limits for pulsed sources were derived with the assumption of a 7-mm, dark-adapted pupil, these exposure limits may be modified for daylight conditions. Modifications are not permitted for exposure durations exceeding 0.5 s.

For $t >$ 10 s the spectrally weighted radiance L_{HAZ} should not exceed the exposure limit for 10 s.

Blue-light photochemical retinal hazard (300–700 nm)

For protection of the retina against photoretinitis, the exposure limit is an effective blue-light integrated radiance $L_B \cdot t$ of 1.0 MJ m^{-2} sr^{-1}, for $t <$ 10,000 s (approx. 2.8 h), where B(λ) is the blue-light hazard function, i.e.,

$$L_B \cdot t = \sum_{300}^{700} L_\lambda \cdot B(\lambda) \cdot t \cdot \Delta\lambda$$
$$\leq 1.0 \text{ MJ m}^{-2}\text{ sr}^{-1} \text{ (effective)} \qquad (6)$$

or

$$L_B \cdot t = \sum_{300}^{700} L_\lambda \cdot B(\lambda) \cdot t \cdot \Delta\lambda$$
$$\leq 100 \text{ J cm}^{-2}\text{ sr}^{-1} \text{ (effective)},$$

and for $t >$ 10,000 s (approx. 2.8 h):

$$L_B \leq 100 \text{ W m}^{-2}\text{ sr}^{-1} \text{ (effective)} \qquad (7)$$

or

$$L_B \leq 10 \text{ mW cm}^{-2}\text{ sr}^{-1} \text{ (effective)}.$$

The maximum direct viewing duration (maximum "stare time"), $t_{\max}$, is found by rearranging eqn (6):

$$t_{\max} = (1.0 \text{ MJ m}^{-2}\text{ sr}^{-1})/L_B \qquad (8)$$

or

$$t_{\max} = (100 \text{ J cm}^{-2}\text{ sr}^{-1})/L_B.$$

For steady fixation of very small sources that subtend a viewing angle less than $\alpha_{\min}$, which is 11 mrad = 0.011 rad for this limit, the blue-light hazard radiance can be converted to an effective irradiance E_B, and the potential hazard may be evaluated by mathematically weighting the spectral irradiance, E_λ, against the blue-light hazard function B(λ) to obtain E_B giving:

$$E_B \cdot t = \sum_{300}^{700} E_\lambda \cdot B(\lambda) \cdot t \cdot \Delta\lambda \leq 100 \text{ J m}^{-2} \qquad (9)$$

or

$$E_B \cdot t = \sum_{300}^{700} E_\lambda \cdot B(\lambda) t \cdot \Delta\lambda \leq 10 \text{ mJ cm}^{-2},$$

and for $t > 10\ 000$ s:

$$E_B \leq 10 \text{ mW m}^{-2} \quad (10)$$

or

$$E_B \leq 1\ \mu\text{W cm}^{-2}.$$

The maximum direct-viewing (fixation) duration, or maximum "stare time," $t_{\max}$, when eqn (9) is not satisfied is found by rearranging eqn (9):

$$t_{\max} = (100 \text{ J m}^{-2})/E_B \quad (11)$$

or

$$t_{\max} = (10 \text{ mJ cm}^{-2})/E_B.$$

Note: The above criteria for evaluating very small sources for exposure durations greater than 100 s would normally be used only for ophthalmic instruments or for a stabilized eye during surgery. For other sources, the use of a measure of the radiance with the limited acceptance angle (field of view) of $\alpha_{\min}$, which increases linearly with time when $t >$ 100 s up to $\alpha = 0.2$ radian at 10,000 s, provides the most appropriate analysis. In effect, because of eye movements involved in normal visual tasks, a maximal value of t for bright sources subtending minimal dimensions and intended to be viewed is 100 s.

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

The third type of retinal hazard—the aphakic photochemical retinal hazard—is encountered very rarely. Guidance for this hazard is provided in the Appendix.

The lens in infants aged less than 2 y transmits more ultraviolet than the adult lens and more protection is needed for the developing retina. Thus the $A(\lambda)$ weighting function should be used for a conservative hazard assessment of light sources to which infants are exposed.

Infrared radiation hazards to the eye (780–3,000 nm)

Cornea and lens. To avoid thermal injury of the cornea and possible delayed effects on the lens of the eye (cataractogenesis), infrared radiation (780 nm $< \lambda <$ 3 μm) should be limited to 100 W m^{-2} (10 mW cm^{-2}) for lengthy exposures (> 1,000 s), and to $18t^{-3/4}$ kW m^{-2} ($1.8\ t^{-3/4}$ W cm^{-2} for shorter exposure durations:

$$E_{\text{IR}} \leq 18t^{-3/4} \text{ kW m}^{-2} \quad (\text{for } t < 1{,}000 \text{ s}) \quad (12a)$$

or

$$E_{\text{IR}} \leq 1.8t^{-3/4} \text{ W cm}^{-2} \quad (\text{for } t < 1{,}000 \text{ s})$$

$$E_{\text{IR}} \leq 100 \text{ W m}^{-2} \quad (\text{for } t > 1{,}000 \text{ s}) \quad (12b)$$

or

$$E_{\text{IR}} \leq 10 \text{ mW cm}^{-2} \quad (\text{for } t > 1{,}000 \text{ s}).$$

Exemption. In cold environments, these limits may be increased to 40 mW cm^{-2} at 0°C and approximately 30 mW cm^{-2} at 10°C for special applications, i.e., where infrared sources are used for radiant heating for reasons of comfort. Lenticular temperature will not exceed 37°C. The relaxation of the limits is based on environmental heat exchange rates for the head (Stolwijk and Hardy 1977), the final temperature of the lens being calculated from ambient temperature.

Retina. For an infrared heat lamp or any near-IR source that provides no strong visual stimulus, the near-IR, or IR-A (780–1,400 nm), irradiance should be limited to:

$$\sum_{780}^{1,400} L_\lambda \cdot R(\lambda) \cdot \Delta\lambda \leq 6{,}000/\alpha \text{ W m}^{-2} \text{ sr}^{-1} \quad (\text{for } t > 10 \text{ s}) \quad (13)$$

or

$$\sum_{780}^{1,400} L_\lambda \cdot R(\lambda) \cdot \Delta\lambda \leq 0.6/\alpha \text{ W cm}^{-2} \text{ sr}^{-1} \quad (\text{for } t > 10\ s).$$

The radiance is not averaged over angles less than $\alpha_{\min} = 11$ mrad. For very large sources α is limited to 100 mrad.

For times less than 10 s, eqn (5) applies.

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 to:

$$H = 20{,}000t^{1/4} \text{ J m}^{-2} \quad (14)$$

or

$$H = 2t^{1/4} \text{ J cm}^{-2}.$$

No limit is provided for longer exposure duration: depending upon initial skin temperature and ambient temperature, 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 (ACGIH 1995).

RADIOMETRIC MEASUREMENTS REQUIRED

General measurement procedures

Detailed measurement procedures and calculation methods are beyond the scope of this document. Suffice it to say that many potential sources of error exist in both broad-band and spectroradiometric measurements, and measurements for optical hazard assessment should not be attempted without some experience in radiometry and an understanding of the importance of measurement geometry (Bauer 1965; Sliney and Wolbarsht 1980;

UNEP/WHO/IRPA 1982; CIE 1987, 1993; McCluney 1984).

Evaluation of potential optical radiation hazard to the eye would ideally involve determination of the spectral irradiance between 200 and 3,000 nm (3.0 μm) at the nearest point of exposure of the eye in order to arrive at a reasonable judgement of exposure duration and the nature of the light source (Sutter et al. 1972; Mayer and Salsi 1979; Sliney and Wolbarsht 1980; McKinlay et al. 1989). Calculated or measured spectral radiance values at wavelengths between 300 and 780 nm are of particular importance in analyzing potential retinal hazards. Spectral irradiance at longer wavelengths could also be measured, although a measurement of total irradiance in the region may be sufficient when the general spectrum is known. Although the $R(\lambda)$ function extends to 1,400 nm, the spectral weighting values are so low that accurate spectral values beyond 1,200 nm may not be required—extrapolation can be adequate if spectroradiometers are insensitive in this spectral region. This spectral radiance can be determined using telescopic receiving optics designed for radiance measurements, or by measuring the spectral irradiance at a fixed distance (e.g., 0.5 m) and dividing by the solid angle Ω subtended by the source, or the solid angle Ω corresponding to the specified radiance averaging angle of 2 min.

$$L_\lambda = E_\lambda/\Omega. \tag{15}$$

The spectral radiance is independent of the viewing distance.

Broad-band optical safety meters. Broad-band optical safety meters have been produced with a spectral response that simulates the $B(\lambda)$ spectral weighting function. These instruments can provide an approximate value for the spectrally weighted effective irradiance or radiance. One of the considerations in deriving the smoothly varying spectral weighting functions (rather than straight-line functions on semi-log paper) was to permit the design of such meters. Such instruments are particularly useful for occupational hygiene survey purposes and for measuring unstable, flickering sources, such as open-arc sources.

Spectroradiometers. Spectroradiometric measurements of optical sources are always preferable in a controlled laboratory setting, particularly when the source is stable. Broad-band meters are calibrated against spectroradiometric measurements of reference lamp sources. However, whenever spectroradiometric measurements are made in the field, confirmatory, quick-check measurements with broad-band meters can reveal possible errors of magnitude. For this reason, it can be useful to check measured spectroradiometric values against measurements of illuminance and spot-luminance. This can also be done by calculating the illuminance E_V or luminance L_V from the spectral irradiance measurements, e.g.,

$$E_V = 683 \sum_{380}^{780} V(\lambda) \cdot E_\lambda \cdot \Delta\lambda, \tag{16}$$

where V(λ) is the CIE photopic response function (CIE 1987).

The luminance L_V is then the illuminance divided by the angular subtense of the source Ω:

$$L_V = E_V/\Omega, \tag{17}$$

where luminance would be expressed in cd m^{-2} if illuminance were expressed in lm m^{-2}.

Limiting apertures and field of view for measurement. Measurements of spectral radiant exposures or spectral irradiances from high-intensity lamps, welding arcs, and other light sources can generally be obtained with spectroradiometric instruments with an aperture of 50 mm or less. If there is concern that localized areas of high irradiance exist, smaller apertures could be employed, but in any case an aperture of less than 7 mm diameter should not be necessary. This aperture diameter does not relate to the rationale for the derivation of the exposure limits (such as an assumed pupil size, which may be smaller) but to known variations in illumination conditions and the fact that the sensitivity of most spectroradiometers would be severely limited by a small aperture.

Note: Smaller apertures are needed to evaluate laser sources because beam diameters are frequently less than 10 mm.

The receptor should have a cosine response for comparison with skin exposure limits. For comparison with retinal hazard exposure limits in the spectral range 380–1,400 nm, only the radiant power or energy arriving at the detector within a field of view of $\alpha_{\min}$ should be measured. This may be accomplished either by using a radiometric hood on the instrument to limit the field of view to $\alpha_{\min}$ or by placing, as close as possible to the light source, an opaque baffle with an aperture that subtends an angle of $\alpha_{\min}$ 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. This measurement arrangement would apply for $\alpha_{\min}$ for durations of 10–100 s. For durations of 1,000 s or more, $\alpha_{\min}$ should be at least 200 mrad for the awake, task-oriented eye.

Far-infrared (IRC) radiation. For all currently known arc and incandescent sources, the contribution made by the IRC 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, but it will be a small fraction of the total integrated spectral 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.

SPECIAL CONSIDERATIONS

Individuals who are being treated with photosensitizing medicines should take additional precautions against excessive exposure to light, as well against UV radiation (for UV guidelines, see Duchêne et al. 1991). Although less of a problem than with UV exposure, photosensitized injury of the skin from light exposure can still be caused by endogenous or exogenous photosensitizers, such as serum bilirubin and phenothiazine. The exposure limits for the skin and eye should normally protect these tissues from photochemical injury, but some extremely photosensitive individuals may experience a reaction even at the exposure limit.

Patients who have been anaesthetized or given mydriatics may experience a higher retinal irradiance during exposure to surgical lights. Recognizing the altered exposure conditions, more stringent limits should be applied for durations greater than 0.5 s.

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.

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 (Court et al. 1978; Hietanen and Hoikkala 1990; Hietanen 1991). Fig. 5 illustrates the relative blue-light retinitis and retinal hazards of viewing typical light sources when eye movement is taken into account. Safety standards for welding have been developed worldwide (Court et al. 1978; Sliney and Wolbarsht 1980; UNEP/WHO/IRPA 1982; ANSI 1989; Sutter 1990; European Committee for Standardization 1992; Suess and Benwell-Morison 1989). In at least one country, lamp safety standards have been proposed which make use of a risk group classification scheme to permit specification of control measures based upon risk posed by the light source (IESNA 1996). For some lamp sources and for open-arc sources, control measures are also necessary for electrical and fire hazards and for airborne contaminants (generally encountered only with welding arcs and other open-arc processes).

CONCLUDING REMARKS

Lamp designs and welding technology are undergoing continuous evolution, using newer, more powerful sources of optical radiation. Because of the rapid growth in the use of new types of special-purpose lamps in science, medicine, and consumer applications, and specialized high-current welding processes in industry, the importance of optical radiation exposure limits will increase. There is a growing need for codes of practice for all potentially hazardous optical sources.

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APPENDIX

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 radiation of approximately 300–400 nm from surgical operating lights. 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. Moreover, UV transmittance of the crystalline lens is much higher in infants under the age of 2 y than in older children and adults.

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 $A(\lambda)$. The approach is to substitute $A(\lambda)$ for $B(\lambda)$ in eqn (6) to (11). For example, the aphakic hazard radiance L_{aphake} is

$$L_{\text{aphake}} = E_{\text{aphake}}/\Omega \qquad \text{(A1)}$$

$$L_A = \sum_{300}^{700} L_\lambda \cdot A(\lambda) \cdot \lambda \leq 1.0 \text{ MJ m}^{-2} \text{ sr}^{-1} \text{ (effective)} \qquad \text{(A2)}$$

or

$$L_A = \sum_{300}^{700} L \cdot A(\lambda) \cdot \Delta\lambda \leq 100 \text{ J cm}^{-1}\text{sr}^{2} \text{ (effective)}$$

for $t \leq 10{,}000$ s (2.8 h).

For values of $A(\lambda)$, see Table 1 (next page).

Table 1. Retinal hazard spectral weighting functions.

Wavelength (nm)	Aphakic[a] hazard function $A(\lambda)$	Blue-light[a] 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	
325	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	0.1
385	2.31	0.013	0.13
390	1.88	0.025	0.25
395	1.58	0.05	0.5
400	1.43	0.100	1.0
405	1.30	0.200	2.0
410	1.25	0.400	4.0
415	1.20	0.800	8.0
420	1.15	0.900	9.0
425	1.11	0.950	9.5
430	1.07	0.980	9.8
435	1.03	1.000	10.0
440	1.000	1.000	10.0
445	0.970	0.970	9.7
450	0.940	0.940	9.4
455	0.900	0.900	9.0
460	0.800	0.800	8.0
465	0.700	0.700	7.0
470	0.620	0.620	6.2
475	0.550	0.550	5.5
480	0.450	0.450	4.5
485	0.400	0.400	4.0
490	0.220	0.220	2.2
495	0.160	0.160	1.6
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
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			$0.2 \times 10^{0.02[(1,1500-\lambda)]}$
1,200–1,400			0.02

[a] The UV extension of $A(\lambda)$ and $B(\lambda)$ at wavelengths below 380 nm are provided for the evaluation of light sources that may contain UV.