EXPECTED CHANGES FOR THE RETINAL THERMAL EXPOSURE LIMITS FOR BRAODBAND INCOHERENT RADIATION OF IEC 62471 AND ICNIRP

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Abstract

Based on recent research, the broadband optical radiation exposure limit for retinal thermal injury can be updated in terms of wavelength dependence, spot size dependence and basic time dependence. The update is scheduled to be published by ICNIRP, the International Commission on Non-Ionizing radiation protection in autumn 2011. In parallel, IEC 62471 and CIE S009 are to adopt their emission limits accordingly.

Introduction

The International Commission on Non-Ionizing Radiation Protection, ICNIRP, specifies exposure limits for safe exposure of the eye and the skin on an international level [1]. These exposure limits are often adopted by national workplace safety legislation (such in the European Union via the Directive on Optical Radiation [2]) and also by product safety standards of the CIE and IEC [3, 4] where product safety *emission* limits are directly derived from the *exposure* limits. At the time of ILSC 2011, the ICNIRP guidelines are accessible for public consultation from the ICNIRP website, and therefore constitute a draft. The limits as discussed in this paper may therefore not be the actual limits that are recommended by ICNIRP in the final and official guidelines to be published in Autumn 2011. Scientific background information on the proposed changes for the spot-size dependence is summarized by Schulmeister et al. [5]

Based on recent experimental injury threshold studies for the eye, it is possible to improve the exposure limits for thermally induced injury of the retina of the eye, in many cases to allow significantly higher exposure levels, i.e. higher product emission levels. The changes intended by ICNIRP and already to a similar degree (but not in identical form) realized by ACGIH [6] (work place safety exposure limits in the USA), will also affect the emission limits for the upcoming new edition of IEC 6247-1.

Current Exposure Limits

The typical hazard from bright broadband sources is *photochemical* injury of the retina following prolonged intentional staring into very bright sources, such as of a welding arc or the sun [7]. Even higher brightness (or radiance) levels are needed so that temperature rises in the retina can lead to thermally induced injury. Retinal thermal injury is therefore the typical damage mechanism for laser radiation [8,9], and only very intense sources of broadband radiation such as high power xenon arc lamps and high power flash lamps can potentially induce thermal retinal injury (where the distance, via the retinal image size, and the pupil diameter also play a crucial role). None-the-less, ICNIRP does specify an exposure limit for retinal thermal injury, which for pulse durations t between 10 µs and 10 s in the current guidelines equals

$$L_{eff} \le 50 \cdot \alpha^{-1} \cdot t^{-0.25}\ kW \cdot m^{-2} \cdot sr^{-1} \qquad (1)$$

The radiance limit is to be compared to the effective radiance L_{eff} where the spectral radiance is weighted with the action spectrum $R(\lambda)$, also referred to as thermal hazard function; this function currently features values larger than 1 in the blue wavelength range, as shown in Figure 1.

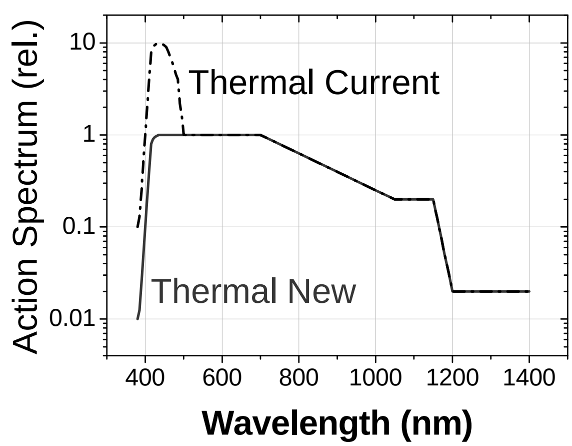

Figure 1. Current and proposed new action spectrum (spectral weighting function) R(λ) for retinal thermal injury.

The exposure limit depends on the diameter of the retinal image, which is characterised by the angular subtense of the source, α. The $1/\alpha$ dependence of the exposure limits extends up to values of α_{max}; for sources larger than α_{max}, the radiance exposure limit does no longer depend on α. The $1/\alpha$ dependence reflects that larger images have reduced radial cooling of the centre of the image and thus for the same irradiance on the retina produce higher retinal temperatures. However, radial cooling takes some time to "reach" the centre of the spot, which is why for large enough sources, the centre of the spot is not affected by radial cooling. This is the regime where the injury threshold and exposure limit becomes independent of the diameter of the image. Currently the value of α_{max} is set to a constant value of 100 mrad (corresponding to a 1.7 mm image on the retina). However, recent studies showed that the dependence of the damage thresholds on spot size can be reflected more accurately by introducing a pulse duration dependent α_{max} as discussed below.

In summary, there are three dependencies: a spot size dependence expressed by the $1/\alpha$ dependence and a maximum angle α_{max}, an exposure duration/pulse duration dependence, and a wavelength dependence, expressed as the weighting function $R(\lambda)$ for the effective radiance that is compared to the exposure limit. All three dependencies are recommended to be changed by ICNIRP, as will be discussed in the following sections.

Retinal Spot Size Dependence

Because of heat flow during the exposure, there is a dependence of the retinal injury threshold on retinal irradiance 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 [10, 11]. It was known from physical principles and from short pulsed laser threshold studies 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 $1/\alpha$ spot size dependence in the current exposure limits was applied up to a critical angle of α_{max} = 100 mrad. Recent thermal model and ex-vivo studies [11] 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 α_{max} to better reflect the retinal irradiance diameter dependence for pulsed sources. The value of α_{max} = 100 mrad still applies for exposure to cw sources, i.e. for exposure durations larger than 0.25 s. The parameter α_{max} is proposed [5] to assume a square-root dependence on pulse duration t for pulse durations between 625 µs and 0.25 s: $\alpha_{max} = 0.2 \cdot \sqrt{t}$ rad, with a value of 5 mrad for pulse durations less than 625 µs and the current value of 100 mrad for pulse/exposure durations above 0.25 s. Therefore, the intended change of the retinal spot size dependence of the exposure limits only affects pulsed sources. The shorter the pulse duration is, the smaller α_{max} becomes. Since the exposure limit decreases with increasing source size up to the critical angular subtense of α_{max}, decreasing α_{max} produces in principle higher exposure limits for sources that at the assessment distance appear larger than α_{max}. In terms of spot size dependence, the maximum difference between the current and the proposed new limits, is a factor of 20 for the case of pulses with pulse duration equal or less than 625 µs (100 mrad/5 mrad = 20).

Exposure Duration Dependence

As a result of the improved understanding of the pulse duration dependence of the spot size dependence of retinal thermal injury, short pulse exposure limits are in principal (in terms of spot size dependence) increased as discussed above. Due to this increase factor of up to 20 in terms of spot size dependence, it was necessary to lower the basic exposure limit for pulsed exposure by a factor of 2.5. This reduction of the exposure limit maintains a minimum reduction factor between injury thresholds and exposure limit of at least 2 for an assumed pupil diameter of 7 mm; the actual overall reduction factor depends on wavelength, spot size and pulse duration and is in many cases larger than 2. For exposure durations greater than 0.25 s (i.e. for continuous wave exposures) for sources which produce a visual stimulus, the closure of the pupil reduces the retinal illuminance [12] 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 also reduce the risk of thermal injury. Based on these effects it was possible to recommend an exposure limit for retinal thermal injury that remains constant at a radiance value of

$$L_{eff} \leq 28 \cdot \alpha^{-1}\, kW \cdot m^{-2} \cdot sr^{-1} \qquad (2)$$

for exposure durations longer than 0.25 s, as shown in Figure 2. In other words, if the exposure from a given cw source is below the exposure limit for an exposure duration of 0.25 s, it also below the exposure limit for longer exposure durations. This is also consistent with the biophysical understanding of the non-linear nature of thermal injury with respect to temperature and linear dependence on pulse duration, (see Paper #901 in these proceedings); the injury threshold has only a very shallow dependence with exposure duration, which is compensated by decreasing pupil diameters.

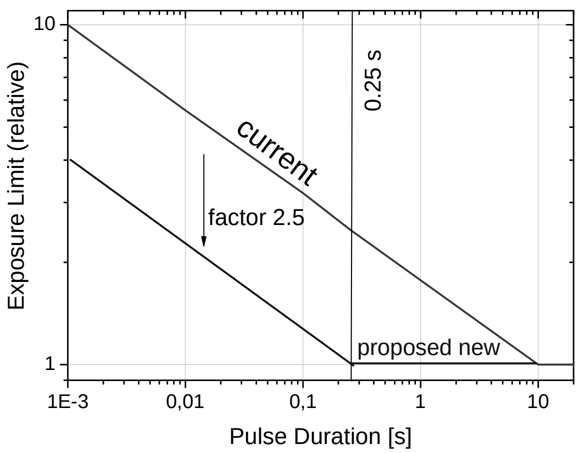

Figure 2. Dependence on pulse/exposure duration for the current and proposed new exposure limits for retinal thermal injury.

The proposed new exposure limits for exposure durations above 0.25 s is equal to the current exposure limit for exposure durations above 10 s.

Spectral Weighting Function R(λ)

Based on a study by Lund et al. 2006 [13] the retinal thermal hazard function $R(\lambda)$ (see Figure 1.) can be corrected. Lund et al. showed conclusively that the originally published thresholds by Ham et al. 1976 and Ham 1989 [14, 15] were one order-of-magnitude too low. This discrepancy is attributed to an error in the dose calculation performed at that time. When the current weighting function was developed, assumed that these values were likely to be a great overstatement 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). The adjustment to the values for $R(\lambda)$ is likely to set $R(\lambda) = 1.0$ for wavelengths from 445 nm to 495 nm and multiplying all values of $R(\lambda)$ from 385 nm to 440 nm by 0.10.

Limit for Low Visual Stimulus

For sources which do not produce a strong visual stimulus ICNIRP (also adopted by IEC 62471) specifies a separate limit. For such sources and exposures, it is not possible to argue with a small pupil for exposure durations longer than 0.25 s and the limit needs to be derived with an assumption of a 7 mm pupil also for longer exposure durations. The pulse duration dependence and the value of the current low-visual-stimulus-limit is not fully inconsistent with these provisions and that the 'normal' retinal limit is also derived with a pupil diameter of 7 mm. The proposed new current low-visual-stimulus-limit is consistent in that it is equal to the 'normal' retinal thermal limit for pulse durations less than 0.25 s, and continues to decrease beyond 0.25 s with the same exposure duration dependence for exposure durations less than 0.25 s, i.e. with

$$L_{eff} \leq 20 \cdot \alpha^{-1} \cdot t^{-0.25} \; kW \cdot m^{-2} \cdot sr^{-1} \qquad (2)$$

This limit and exposure duration dependence applies until the limit reaches the level of the current low-visual-stimulus-limit, which happens to be at approximately 100 s (the exact value of the limit at 100 s equals 6325 W m^{-2} sr^{-1}). For exposure durations longer than 100 s, the exposure limit is kept at the constant value of 6000 W m^{-2} sr^{-1} (thus there is a discontinuity of 5 % at 100 s).

The wavelength weighting (action spectrum) and the spot size dependence of the low-visual-stimulus-limit is the same as for the 'normal' limit.

Discussion – Impact of Changes

The change of the exposure limits as discussed in this paper can in principle have an impact both on an exposure limits assessment (such as at the workplace or for product safety) and/or on risk group classification according to IEC 62471. IEC 62471 is updated in parallel with the ICNIRP exposure limits and is scheduled to be published as IEC 62471-1 (Edition 2) by the end of 2012 or in the first half of 2013. The new limits can be used as state of the art and technology for safety analysis of products even before the amendment of IEC 62471 becomes official, which is not before the end of 2012.

For IEC 62471, the proposed changes, where the retinal thermal limit is a constant radiance value for exposure durations longer than 0.25 s, will have the impact that a given lamp or LED is either Risk

Group 3 or falls in the exempt group (in the future also referred to Risk Group 0).

It depends on the pulse/exposure duration, wavelength distribution and angular subtense of the apparent source at the assessment distance in what way the proposed changes of the retinal exposure limits will affect a given source or exposure.

Due to the change of the action spectrum it will depend on the blue component of the spectrum how strongly a given source is affected (concerning the retinal thermal exposure limit; often, the photochemical exposure limit is the more restrictive one); blue LEDs will be strongly affected and the reduction of the action spectrum allows in effect an increase of output power/exposure of a factor of 10. For typical white sources, the reduction of the action spectrum in the blue will have a net-effect of an increase of the allowed power of roughly 2 (the actual factor depends on the colour temperature). For cw sources, this will make the photochemical retinal limit (which remains unchanged) even more critical. If the blue component is filtered out of the lamp, such as is usually the case for IPL systems, this change will have no effect.

Regarding the change of the exposure duration dependence, for exposure durations of 10 s and above (i.e. Risk Group 1 and Exempt Group of IEC 62471), the current and proposed new limit are equal and, besides the change of the action spectrum, there is no change. For continuous wave lamps and exposure durations of 0.25 s (the time base for Risk Group 2), there is a reduction in the basic limit of a factor of 2.5. Since the spot size dependence remains unchanged for this time base, it will depend on the spectral distribution if there is an overall increase or decrease of the allowed emission/exposure level: for white light sources, the reduction of the action spectrum and the reduction of the time dependence of the exposure limit roughly compensate each other. For cool white spectra or blue LEDs, the overall effect will be an increase of the allowed emission/exposure level.

For pulsed sources, the overall effect, besides the change in action spectrum, will depend on the pulse duration t and the angular subtense of the source α relative to the value of $\alpha_{max}(t)$. For the example of a white flashlight, the decrease of the action spectrum compensates roughly for the basic decrease of the exposure limit of 2.5. If the angular subtense is larger than α_{max}, for instance for a 2 ms pulse duration larger than 9 mrad), there is an overall increase of the allowed emission/exposure level.

For small pulsed LEDs in the mid-green, yellow or red wavelength range (where the change of the action spectrum does not have an effect), the proposed amended exposure limits might be more restrictive (up to a factor of 2.5) since the change in spot size dependence only affects sources that are larger than α_{max}. However, in a scenario where an LED is small (either because it is a bare small chip, or it is at some distance) it is not expected that LED technology can produce radiances which approach the exposure limit any time soon; for small sources, as long as they are not lasers, the emission might be 'radiance limited' and it is therefore difficult, if not impossible, to produce emitters that are both small and produce radiances that can approach the emission limit (see also discussion in the ICNIRP Statement on LEDs [16]).

Regarding the low-visual-stimulus-limit, the limit for 10 s increases (additionally to any effect that the amendment of the spot size dependence might have for pulsed emission) since the current constant value of 6000 W m^{-2} sr^{-1} is replaced by an exposure duration dependent value, which for 10 s equals about 11 000 W m^{-2} sr^{-1}, an increase of almost a factor of 2.

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Meet the Author

Karl Schulmeister, PhD, is a consultant on laser and broadband radiation safety at the Seibersdorf Laboratories, where also a specialised accredited test house is operated. In the last years, a computer model was developed to quantitatively predict retinal, corneal and skin injury, which can be used for product risk characterisations independent of exposure limits.

Karl Schulmeister is a member of ICNIRP, the commission responsible for developing exposure limits for laser and broadband radiation on an international level. He is also member of CIE TC 6-47 as well as IEC TC 76 WG9, the workings groups that are responsible for developing the international lamp safety standard IEC 62471. The research interest of his group in the last six years concentrated on retinal thermal injury, and the changes discussed in this paper are largely based on this work.

Reference Information

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