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# COMPARISON OF CORNEAL INJURY THRESHOLDS WITH LASER SAFETY LIMITS

Paper #303

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## Abstract

A computer model that predicts thresholds for laser induced corneal injury in the infrared wavelength range was used to systematically analyze wavelength, pulse duration and beam diameter dependencies. The thresholds were compared with the respective maximum permissible exposure (MPE) values promulgated by ANSI Z136.1-2014, ICNIRP 2013 and IEC 60825-1:2014, with an emphasis on the wavelength range of 1250 nm to 1400 nm, where a limit additional to the retinal limit is needed to protect the cornea. The ANSI standard features a dedicated limit to protect the cornea for wavelengths less than 1400 nm, ICNIRP recommends to use the skin MPEs, and IEC 60825-1:2014, for classification of laser products as Class 1, specifies Class 3B AELs as dual limit. Comparison with injury thresholds shows that the ANSI MPEs provide for an ample reduction factor for all wavelengths. Due to the 7 mm aperture stop defined in IEC 60825-1, levels permitted by the Class 3B limit exceed predicted injury thresholds for small beam diameters and wavelengths between about 1350 nm to 1400 nm even for short exposure durations so that in this case, the Class 3B AEL does not appear to be an appropriate limit. For beam diameters of about 4 mm and larger and wavelengths of less than about 1360 nm, the Class 3B limit affords sufficient protection. For the skin MPEs, the margin between corneal injury thresholds and MPEs decreases steadily for wavelength approaching 1400 nm. However, normal eye movements can be expected to reduce the effective exposure to remain below injury thresholds so that the skin MPEs can serve as adequate and simple dual limit to protect the cornea for wavelengths less than 1400 nm.

## Introduction

This proceedings paper does not contain the results of the threshold calculations and the discussion. The full paper was submitted to the Journal of Laser Applications [1].

Exposure limits for laser radiation to protect the eye are promulgated on the international level by ICNIRP [2] and in the USA in ANSI Z136.1 [3]. Product safety emission limits for Class 1 are directly derived from the ICNIRP exposure limit values and are stated in the international laser product safety standard [4] IEC 60825-1. Exposure limits to protect the cornea are historically based on injury thresholds obtained with rabbit and non-human primate models. The injury thresholds show a strong dependence on wavelength and pulse duration but also to a degree on the diameter of the laser beam incident on the cornea. The wavelength region of about 1050 nm to 1400 nm is a transition zone where the outer ocular media are relatively transparent at 1050 nm and highly absorptive at 1400 nm. As a result, the location of the eye injury at threshold level is the retina for 1050 nm and transitions to the cornea for wavelengths approaching 1400 nm. Recent inclusion of a correction factor for the retinal MPEs that reflects the sharp increase in absorption in the outer ocular media results in high retinal MPEs, making an additional limit to protect the cornea necessary.

A computer model to predict corneal laser induced injury thresholds was developed at Seibersdorf Laboratories, described elsewhere [5, 6]. The model has been fully validated against all relevant experimental injury thresholds. The maximum deviation of the ratio of the model predictions compared to the experimental injury thresholds was found to be 1.7 (i.e. to the "unsafe" side), the maximum deviation where the model predicted a lower threshold as compared to the experimental thresholds was 2. The model predictions for single pulses are used in this paper for a comprehensive comparison with the MPEs, particularly with the updates of ANSI Z136.1 and IEC 60825-1 from 2014. The comparison can serve as basis for laser safety committees to consider possible improvements of the MPEs and product safety limits. Particular emphasis is given to the wavelength range of 1200 nm to 1400 nm where the latest editions of the standards feature specific limits to protect the cornea. A comparison of multiple pulse thresholds against the respective MPE values can be found in another ILSC 2019 proceedings paper [7].

For a review and a discussion of the physiology of the cornea and injury thresholds of the cornea in the infrared wavelength range, we refer to References [6, 8].

## Exposure and Classification limits

### Overview

Exposure limits to protect the eye are defined in the laser safety standards IEC 60825-1 [4], ANSI Z136.1 [3] and the ICNIRP [2] guidelines (in the following, these are also sometimes referred to as "IEC", "ANSI" and "ICNIRP", respectively). The term "exposure limits" (abbreviated to EL) is used by ICNIRP and the term "maximum permissible exposure" (abbreviated to MPE) is used in ANSI and IEC, but the numerical values in most cases are the same; differences are discussed in the following. IEC 60825-1 lists the MPEs, as "copy" from the ICNIRP EL, in an informative annex. The "accessible emission limits" (AEL) for classification of products as Class 1 defined in IEC 60825-1 limit the power or energy emitted by the device. Thus Class 1 AELs are product safety limits and not exposure limits. However, numerically, they are equal to the MPEs for the eye multiplied by the area of the defined limiting aperture; see for instance [9-11] for further discussion. Consequently, the discussion on IEC MPEs also applies to the ELs of ICNIRP as well as to the AEL of Class 1 defined by IEC 60825-1. The usage of AELs by ANSI is similar to the IEC AELs. However, ANSI Z136.1 is not a product safety standard.

In the time-frame of 2013 to 2014, some of the exposure limits promulgated by IEC, ANSI and ICNIRP were updated. Compared to earlier editions, the limits to protect the cornea for exposure to laser radiation with wavelengths above 1500 nm were not changed. Relevant for this paper is the significant increase of the MPEs to protect the retina in the wavelength range between 1250 nm to 1400 nm. Before the 2013/2014 revision, the retinal limit, defined in the retinal hazard wavelength range of 400 nm to 1400 nm, was low enough so that the cornea was not at risk as long at the exposure of the eye was below the retinal limit[1]. In earlier editions, there was a "clean cut" at 1400 nm, between the limit to protect against injury of the retina for shorter wavelengths and injury to the cornea at longer wavelengths. The 2013/2014-increase of the retinal limits in the wavelength range of 1200 nm to 1400 nm made it necessary to define additional limits in order to protect the cornea (i.e. in that wavelength range, due to the strong absorption of the pre-retinal media, the cornea can be damaged at levels that are below exposure limits for the retina). This "dual" MPE to protect the cornea in the wavelength range below 1400 nm was defined in ICNIRP/IEC differently as compared to ANSI. In IEC, for the classification of products, the dual AEL for the emission of a Class 1 product was defined as equal to the Class 3B limits. The limits (table 1) are discussed in detail in the following subsections.

### MPEs to protect the cornea

In order to protect the cornea for wavelengths in the range of 1200 nm to 1400 nm, the ANSI committee developed dedicated MPEs for the cornea, extending the corneal MPE (that in earlier editions applied only for wavelengths longer than 1400 nm) down to 1200 nm. In this process, for pulses, the corneal MPEs were increased for wavelengths above 1400 nm, so that the ANSI corneal MPEs avoid a step function at 1400 nm. For wavelengths less than 1400 nm, the ANSI MPEs to protect the cornea feature a wavelength dependence expressed by the factor $K_\lambda$, which ranges from $K_\lambda = 100$ at 1200 nm to $K_\lambda = 1$ at 1400 nm (see figure 1). The ICNIRP 2013 revision recommended (footnote d of Table 5 of that document) to apply the MPEs for the skin to protect the cornea[2]. IEC 60825-1 in the footnote to the MPE tables A.1 to A4 of that document, notes: *"In the wavelength range between 1 250 nm and 1 400 nm, the limits to protect the retina given in this table may not adequately protect the anterior parts of the eye (cornea, iris, and lens ) and caution needs to be exercised. There is no concern for the anterior parts of the eye if the exposure does not exceed the skin MPE values."* The IEC and ICNIRP recommendation to use

[1] For exposure to highly divergent beams at very close distances, for large retinal image sizes and relatively deeply penetrating wavelengths, the iris and lens can be at risk even though the exposure is below earlier retinal thermal limits; IEC and ANSI introduced corresponding guidance already in the pre-2013/2014 editions, and this issue is not the scope of this paper.

[2] ICNIRP refers to two-times the skin MPE for the infrared wavelength range but then notes that for a general safety analysis, both the skin and the eye limit has to be considered. It is logical that due to blinking, defining higher MPEs for the eye as for the skin is only relevant for the case when there is no blinking, i.e. in medical eye procedures.

the skin MPEs to protect the cornea for wavelengths shorter than 1400 nm creates a step function at 1400 nm for exposure durations exceeding 1 ms, as the skin MPEs at 1400 nm are a factor of 10 higher than the corneal MPEs at 1400 nm (in contrast to ANSI, the IEC/ICNIRP corneal MPEs were not adjusted for wavelengths above 1400 nm).

Table 1. MPE values for infrared wavelengths greater than 1200 nm and exposure durations exceeding 1 ns. For comparison with experimental threshold data, which is traditionally given in terms of "per cm$^2$", all limits are expressed in terms of "per cm$^2$" even though IEC and ICNIRP specified the MPEs in terms of "per m$^2$".

| **Wavelength** [nm] | **Exposure Duration** | **"Corneal" MPE ANSI** | **"Corneal" MPE IEC/ICNIRP** |
|---|---|---|---|
| 1200 - 1400 | 1 ns – 100 ns | 0.3 $K_\lambda$ J cm$^{-2}$ | 0.02 $C_4$ J cm$^{-2}$ # |
| | 100 ns – 1 ms | | 1.1 $C_4$ $t^{0.25}$ J cm$^{-2}$ # |
| | 1 ms – 4 s | 0.3 $K_\lambda$ +0.56 $t^{0.25}$ - 0.1 J cm$^{-2}$ | |
| | 4 s – 10 s | 0.3 $K_\lambda$ + 0.7 J cm$^{-2}$ | |
| | >10 s | 0.03 $K_\lambda$ + 0.07 W cm$^{-2}$ | 0.2 $C_4$ W cm$^{-2}$ # |
| 1400 - 1500 | 1 ns - 1 ms | 0.3 J cm$^{-2}$ § | 0.1 J cm$^{-2}$ $ |
| | 1 ms - 4 s | 0.56 $t^{0.25}$ + 0.2 J cm$^{-2}$ § | 0.56 $t^{0.25}$ J cm$^{-2}$ $ |
| | 4- 10 s | 1 J cm$^{-2}$ § | |
| | >10 s | 0.1 W cm$^{-2}$ §$ | |
| 1500 - 1800 | 1 ns - 10 s | 1 J cm$^{-2}$ | |
| | > 10 s | 0.1 W cm$^{-2}$ | |
| 1800 - 2600 | 1 ns - 1 ms | 0.1 J cm$^{-2}$ | |
| | 1 ms - 10 s | 0.56 $t^{0.25}$ J cm$^{-2}$ | |
| | >10 s | 0.1 W cm$^{-2}$ | |
| 2600 - $10^6$ | 1 ns -100 ns | 0.01 J cm$^{-2}$ | |
| | 100 ns - 10 s | 0.56 $t^{0.25}$ J cm$^{-2}$ | |
| | >10 s | 0.1 W cm$^{-2}$ | |
| Correction factors | | $K_\lambda = 10^{0.01(1400-\lambda)}$ for ANSI<br>$C_4$ = 5 from 1050 to 1400 nm for IEC (referred to as $C_A$ in ICNIRP) | |

# ICNIRP and IEC recommended that the skin limit be applied as a dual limit to the retinal thermal limits (footnote d for Table 5 in the ICNIRP 2013 guidelines; footnote f for Table A.4 in IEC 60825-1:2014). For wavelengths less than 1400 nm, ANSI defines the same MPEs as ICNIRP/IEC to protect the skin, but has "special" MPEs to protect the cornea.

§ These limits are also defined by ANSI as skin MPEs; ANSI developed dedicated limits to protect the cornea for wavelengths less than 1400 nm.

$ These limits are also defined by ICNIRP and IEC as skin MPEs; ICNIRP and IEC recommend application of the skin MPEs to protect the cornea for wavelengths less than 1400 nm.

In figures 1 and 2, the ANSI and IEC/ICNIRP MPEs are compared and it is interesting to note that for wavelengths slightly less than 1400 nm, the skin MPE limits (and therefore the IEC/ICNIRP dual limit to protect the cornea), for 10 second exposure duration are a factor 10 higher than the ANSI corneal limits; for 1 second exposure duration the difference is a factor of 5. Because the ANSI corneal limits have a wavelength dependence in this wavelength regime while the skin limits do not have a wavelength dependence, the skin limits are lower than the ANSI corneal limits for wavelengths below 1250 nm for 10 seconds exposure duration; for 1 second exposure duration, the skin limits are lower than the ANSI corneal limit for wavelengths below 1280 nm. For an exposure duration of greater than 10 seconds for retinal point sources (and exposure durations greater than $T_2$ for extended sources), note 5 of Table 5c and note 6 of Table 5f in the ANSI standard states that the skin MPE value is not to be exceeded. This can be seen as an additional limit to the specific limit defined to protect the cornea. Consequently, for wavelengths less than 1250 nm, where the corneal limit is higher than the skin limit for exposure durations of 10 seconds and longer, there are effectively two dual limits to protect the cornea.

We show in figure 1 and 2 that while the ANSI corneal limits have a significant dependence on wavelength, the skin limits and the Class 3B limits do not. On the other hand, the skin limits as shown in figure 2 feature a pronounced dependence on exposure duration while the Class 3B limits and the ANSI corneal limits for wavelengths less than 1400 nm have a relatively weak exposure duration (or, for AEL, "emission duration") dependence.

In the process of defining a specific corneal limit for wavelengths less than 1400 nm, the ANSI corneal MPE for wavelengths between 1400 nm and 1500 nm and for pulse durations shorter than 1 ms was increased by a factor of 3 compared to the earlier MPE. For exposure durations of 10 seconds, the ANSI limits for wavelengths above 1400 nm remained unchanged, and are therefore also equal to the ICNIRP and IEC limits (compare the two orange curves in figure 2). While ICNIRP kept the earlier MPEs for wavelengths between 1400 nm and 1500 nm, ANSI also adjusted the limits in that wavelength range for exposure durations shorter than 10 seconds, so that for the ANSI cornea limit, there is no step-function at 1400 nm. ANSI also adjusted the skin limits in the wavelength range of 1400 nm to 1500 nm to set them equal to the new corneal limits. This, however, means that the ANSI skin limits also have a step function at 1400 nm, as ANSI kept the earlier skin limits for wavelengths less than 1400 nm.

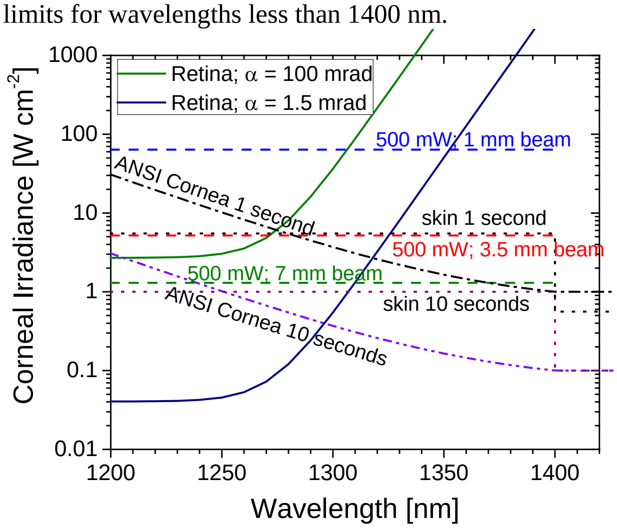


Figure 1. MPE values as function of wavelength for exposure durations of 10 seconds and 1 second (the retinal MPEs are only shown for 10 seconds) in the wavelength range below 1400 nm, where a new dual limit was necessary due to the increase of the retinal limit. Also the dual limits for classification as Class 1 according to IEC 60825-1:2014 are shown, which (as a limit additional to the Class 1 retinal limit) refer to the Class 3B limit (500 mW) to protect the cornea. Here, the skin MPE and the ANSI cornea MPE values are not "scaled" to consider the effect of beam diameters smaller than the limiting aperture, i.e. as the limits are plotted, they apply to beam diameters that are larger than the limiting aperture.

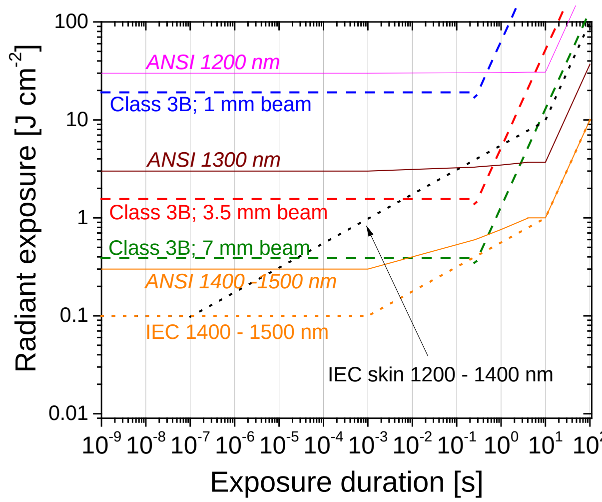


Figure 2. MPEs as function of exposure duration for wavelengths less than 1500 nm. Also the dual limits for classification as Class 1 according to IEC 60825-1:2014 are shown, which (as a limit additional to the Class 1 retinal limit) refer to the Class 3B limit to protect the cornea. With the exception of the Class 3B limit, the other limits are not "diameter-scaled", i.e. as the "ANSI" and "IEC" limits are plotted, they apply to beam diameters that are larger than the limiting aperture.

Figure 3 shows the MPEs as function of exposure duration applicable to wavelengths above 1400 nm. For an exposure duration of 10 seconds, the MPE for all wavelengths above 1400 nm equals 0.1 W $cm^{-2}$ (1000 W $m^{-2}$) which is equivalent to $1 \cdot t$ J $cm^{-2}$. For the wavelength range of 1500 nm to 1800 nm, this radiant exposure MPE is kept for all exposure durations down to 1 ns, while for other wavelengths, the MPE expressed as radiant exposure per exposure duration decreases for shorter pulses and reaches the "no exposure duration dependence" level at different exposure durations.

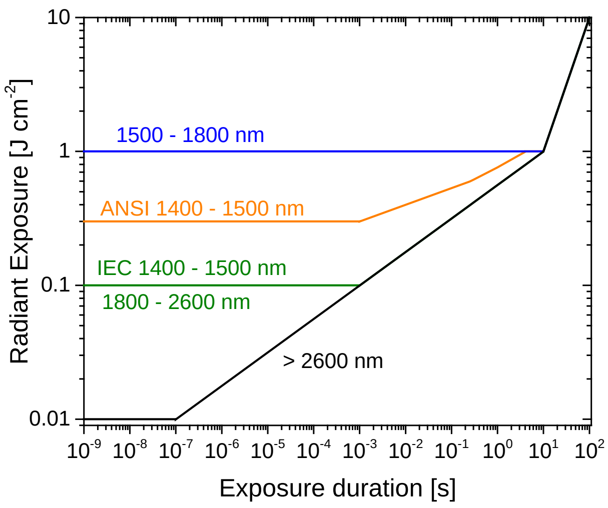


Figure 3. The MPEs as function of exposure duration for wavelengths exceeding 1400 nm.

## Measurement apertures

For a safety assessment of ocular and skin exposure, the values of the MPEs are relevant, as well as, for small beam diameters or hotspots, the averaging apertures that are defined for the determination of the irradiance or radiant exposure level. While the term used in ANSI and ICNIRP for these apertures is "limiting apertures", in terms of radiometric effect [9, 11] it is really an *averaging* aperture, since the irradiance and radiant exposure is averaged over the respective aperture, i.e. the irradiance is determined by dividing the power that passes through the aperture by the area of the aperture. When the beam is smaller than the aperture, or when there are hotspots smaller than the aperture, the averaged irradiance is smaller than the actual irradiance. Thus, due to the averaging aperture, the exposure level that is compared against the MPE is reduced compared to the actual corneal irradiance. This is relevant for the comparison of the MPEs with injury thresholds, since when the *averaged* exposure level is equal to the MPE, the *actual* exposure of the cornea (at least when there are no eye movements) can be higher than the MPE and thereby be closer to the injury threshold than the MPE value implies. When irradiance hotspots or beam diameters are smaller than the aperture, the averaging aperture has the effect of reducing the margin between the exposure level permitted by the MPE and the injury threshold. For instance, if the beam profile on the cornea is a top-hat with a diameter of 1 mm and the averaging aperture has a diameter of 3.5 mm, the actual irradiance is a factor of $3.5^2$ higher than the averaged radiance. The effect of the averaging aperture has to be accounted for in a comparison of injury thresholds with MPEs in combination with eye movements. Recently, in research papers on skin injury, the thresholds were corrected, considering this effect of the averaging aperture [12]. However, instead of decreasing the injury threshold by the respective factor, for the comparison with injury thresholds, we prefer to increase the MPE with that factor, such as for the example of a 1 mm beam and an exposure duration of 10 seconds, a factor of 12.3. We prefer this approach, since the experimental injury threshold is given by physical and biological properties that are not related or influenced by the averaging apertures defined in the standards. The averaging apertures are defined by ANSI or ICNIRP committees together with the MPEs, as rules for how to perform an MPE analysis. Thus it appears more appropriate for a comparison of MPEs with injury thresholds, to leave the injury thresholds as experimentally or computationally determined (with a stabilized eye), but increase the MPEs instead. The MPEs that - for beam diameters smaller than the limiting aperture - are increased with the ratio of the area of limiting aperture to the area of the beam are in this paper referred to as "scaled" MPEs. This scaling is only necessary for the comparison of biological thresholds with MPEs. For a workplace hazard analysis (being based on MPEs and not on injury thresholds), the MPEs would be used as defined and it is the exposure level that is "scaled" (averaged by the measurement aperture). The overall effect for both approaches is the same, namely decreasing the ratio between the injury threshold and the corneal exposure level that is permitted by the MPE for the assumption of a stationary beam and a stationary "target" (which for 10 second exposure durations for normally behaving humans is not applicable).

The averaging (limiting) aperture for the determination of corneal and skin exposure levels for comparison with the respective MPEs are defined in an equivalent way in the ANSI, ICNIRP and IEC documents, but compared to IEC and ICNIRP, the ANSI standard specifically refers to limits to protect the retina, cornea and skin (Table 8a of ANSI) when defining the diameter of the limiting aperture. All standards define a 7 mm limiting aperture for the retinal MPE analysis from 400 nm to 1400 nm as well as a constant diameter of 3.5 mm for the skin MPE analysis for wavelengths up to 100 µm. For wavelengths above 1400 nm, for the MPEs to protect the eye (i.e. the cornea), all standards define an averaging aperture where the diameter depends on exposure duration[3]: the diameter equals 1 mm for exposure durations up to 0.35 seconds (0.3 seconds in ANSI), and then increases with a $t^{3/8}$ dependence to a diameter of 3.5 mm for an exposure duration of 10 seconds. The main rationale for the increasing averaging aperture for the determination of the corneal exposure level is assumed eye movements that result in a decrease of the effective relevant exposure level. It is clear that with the exception of medically immobilized eyes, a certain extent of eye movements can be assumed for a 10 second exposure duration so that the increase of the averaging aperture diameter appears justified. In turn this means that increasing the MPE with the ratio of averaging aperture area to beam area, as done in the analysis below, for 10 second exposure duration, can be considered as "unfair", as it assumes a stationary beam and a stationary target. Therefore, for a more balanced discussion, more weight is placed on the exposure duration of 1 second, where the averaging aperture has a diameter of 1.5 mm and where the eye movements relative to a beam that is assumed stationary (as worst case assumption) might be small.

Table 8a of ANSI specifies the exposure-duration-dependent limiting aperture generally for the cornea including for the case of wavelengths less than 1400 nm. For the dual limit to protect the cornea in the wavelength range of 1200 nm 1400 nm, IEC and ICNIRP recommend using the skin limit for that purpose, and have not specifically defined what averaging aperture to use for the measurement to be compared against the skin MPE. Since the exposure-duration-dependent aperture (with 1 mm diameter for pulses) is defined to protect the cornea for wavelengths above 1400 nm, from biophysical principles it would stand to reason to conservatively apply this exposure-duration-dependent aperture to also protect the cornea for wavelengths less than 1400 nm, and not the 3.5 mm aperture that is defined for skin hazard analysis. The "diameter-scaling" of the MPEs in this paper was generally done on the basis of the exposure-duration-dependent limiting aperture, also for the case of the skin MPEs recommended by ICNIRP and IEC. For the respective plots, it has to be kept in mind that a 3.5 mm aperture for a 1 mm beam, compared to a 1 mm aperture for up to 0.3 s or a 1.5 mm aperture for 1 s, has a significant effect in scaling the MPEs.

### Class 3B AEL as "dual limit"

For the classification of products as Class 1, Class 1M or Class 3R, the limit to protect the anterior parts of the eye (as dual limit additional to the retinal thermal limit) for wavelengths between 1250 nm and 1400 nm was set as the AEL of Class 3B where the accessible emission is measured through a 7 mm diameter aperture at the location where the accessible emission for the retinal thermal AEL is determined. For cw emission (emission duration longer than 0.25 s), the AEL of Class 3B in that wavelength range equals 500 mW, for emission durations between 1 ns and 0.25 s, the AEL of Class 3B equals 0.15 Joule. For comparing the corneal exposure that is permitted by the Class 3B AEL against injury thresholds, it has to be kept in mind that varying beam diameters at the cornea can result in drastically varying corneal irradiance levels. For a beam diameter of 7 mm, 500 mW corresponds to 1.3 W $cm^{-2}$, for a beam diameter of 3.5 mm to 5.2 W $cm^{-2}$ and for a beam diameter of 1 mm to 64 W $cm^{-2}$, respectively. These levels, derived from the Class 3B AEL are also shown in figures 1 and 2. We see that for a 7 mm beam diameter (or larger) the 500 mW limit is very close to the skin MPE for an exposure duration of 10 seconds. For a 3.5 mm beam, the "diameter-scaled" (to consider the effect of the measurement aperture) Class 3B limit is almost equal to the skin MPE for an exposure duration of 1 second, and for a 1 mm beam, the Class 3B limit of 500 mW is equal to the skin MPE for an exposure duration of 35 ms.

## Optical properties of the cornea

The wavelength dependence of the absorption depth of optical radiation in the cornea is the basis for the discussion of the injury thresholds as function of wavelength, particularly for short exposure (pulse) durations. For longer exposure (pulse) durations, heat flow evens out the strongly varying absorption depth, as further discussed below.

For wavelengths up to 2500 nm, experimental absorption data are available for the cornea, aqueous and lens of the non-human primate as reviewed by Lund et al. for the *International Commission of Illumination* [13]. Between 2500 nm and 20 µm, specific absorption values for the anterior parts of the eye are not available but can be assumed to be equivalent to that of water, as shown in figure 4. The optical absorption depth (defined as the level where the local irradiance is a factor of 1/e of the irradiance incident on the surface) for the cornea in the infrared wavelength range has a very strong

[3] Thus, while the MPEs are the same for the skin and eye for wavelengths above 1400 nm, the averaging aperture is different, which can make a difference for exposure to pulses when the diameter of the beam is smaller than 3.5 mm or has irradiance hot-spots.

dependence on wavelength and varies from 1 cm at a wavelength of 1000 nm to an absorption depth of 1 µm (i.e. within the tear layer) at 3 µm wavelength. For wavelengths of 2500 nm and longer, the incident radiation is completely absorbed within the cornea. This strong variation with wavelength has a corresponding impact on the temperature increase for a given irradiance level at the cornea and therefore on the injury threshold.

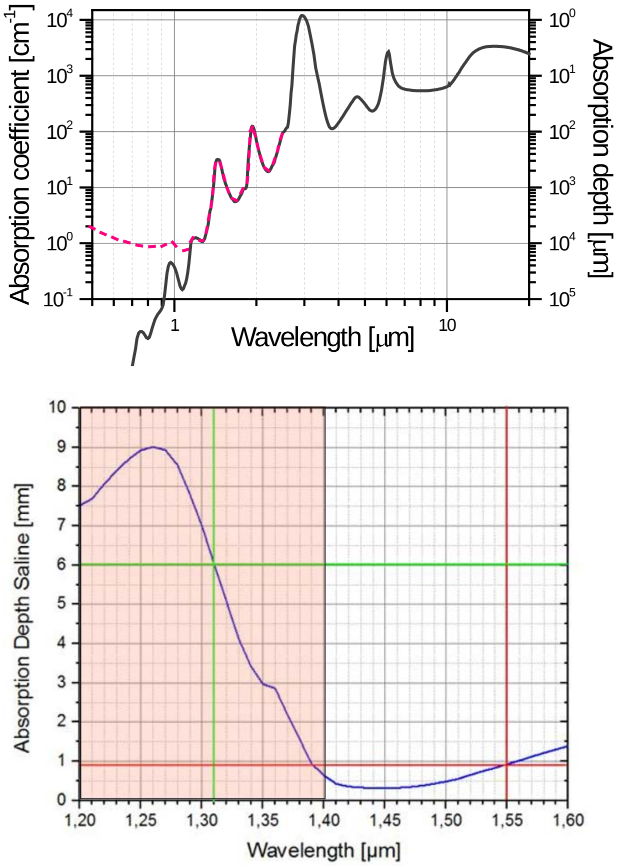


Figure 4. Absorption coefficient and absorption depth for the cornea (dashed line [13]) and for water (solid line [14]). An exponential dependence of the local irradiance profile (Beer Lambert law) is assumed. In b), the section between 1200 nm and 1600 nm is shown on a linear scale plotted as absorption depth in mm, to highlight the steady decrease of absorption depth for wavelengths approaching 1400 nm (the wavelengths of 1310 nm and 1550 nm are associated to crosshairs).

## Results and Discussion

For the presentation of the injury thresholds and the detailed comparison with MPEs, see the paper submitted to Journ. Laser Appl. [1].

## Summary and Conclusions

A systematic comparison of computer-model injury thresholds with the MPEs specified by ANSI Z136.1, IEC 60825-1 and ICNIRP was performed [1]. For wavelengths above 1500 nm, the limits in these three documents are the same. The smallest factor between threshold and MPE was found to be 4 for strongly absorbing wavelengths and exposure durations around 10 ms, both for small and larger beam diameters. Between 1400 nm and 1500 nm, for exposure durations less than 10 seconds, the ANSI limits are higher than the ICNIRP/IEC limits by up to a factor of 3; the reduction factor is sufficient also for this wavelength regime.

Due to the significant increase of the retinal thermal limits for wavelengths between 1300 nm and 1400 nm in the 2013/2014 revision, it became necessary to introduce an additional limit to protect the cornea in that wavelength range. The IEC and ICNIRP guidelines recommend using the skin limits, while ANSI introduced a specific limit to protect the cornea. The ANSI limit follows the trend of injury threshold with wavelength and pulse duration well and the reduction factor is at least 7. While ANSI specifies exposure-duration-dependent averaging apertures to be used for wavelengths less than 1400 nm, ICNIRP and IEC give no specific guidance on the diameter of the averaging aperture to be used for the assessment of the ocular exposure that is to be compared against the skin MPE values. A comparison of irradiance levels that would be permitted for a 3.5 mm aperture with injury thresholds clearly shows that averaging over 3.5 mm for smaller beam diameters and wavelengths tending towards 1400 nm is not permissible; this should have been expressed specifically in the ICNIRP and IEC guidelines; the exposure-duration-dependent averaging aperture as defined for the eye for wavelengths exceeding 1400 nm should be used.

Due to the lack of wavelength dependence of the skin limits but reduced injury thresholds for wavelengths approaching 1400 nm, when using the skin MPEs as dual limit, the reduction factor is relatively small for wavelengths close to 1400 nm, but should be sufficient to avoid injury. For a 4 mm beam diameter, the reduction factor is about 4 for 10 s exposure duration and of the order of 3 when the hazard analysis is based on a 1 s exposure duration, i.e. using the MPE for $t = 1$ s. Using 10 s exposure duration for the MPE analysis (which is the typical value), for a 1 mm beam diameter and an averaging aperture of 3.5 mm, the permitted actual irradiance is, for wavelengths close to 1400 nm, equal to the injury threshold when there are no eye movements. However, eye movements, both natural as well as from aversion responses, for such small beams will smear out the exposure and reduce the effective irradiance, so that it should be acceptable to apply the skin MPE as dual limit also in this case, although the margin to injury does not appear large. With an exposure relatively close to the injury threshold it is not clear what the pain sensation is going to be: for the case that the pain is excessive or noxious, even when due to aversion responses an actual burn is avoided, such a high level of permitted exposure might not be seen as appropriate at exposure levels of an exposure limit.

For the Class 3B dual limit as defined by IEC 60825-1 Edition 3.0 for Class 1 laser products and the accessible emission measured with a 7 mm aperture at 100 mm distance from the reference point, the situation is more critical. A power of 500 mW is permitted to pass through a 7 mm aperture for emission durations longer than 0.25 s irrespective of the wavelength. Due to the measurement aperture of 7 mm, the issue is more critical for small beam diameters of for instance 1 mm incident on the cornea. While the irradiance permitted by the Class 3B limit for a 7 mm beam is well below the injury threshold also for wavelengths close to 1400 nm, the irradiance permitted for a 1 mm beam for wavelengths approaching 1400 nm exceeds the injury threshold within 0.25 seconds - an exposure duration where it is not applicable to argue with significant eye movements. For the wavelength of 1350 nm common in telecommunication, the Class 3B limitations appear sufficient to protect the cornea provided the beam diameter at the exposure distance is larger than 4 mm. It follows that two aspects of Class 3B AELs as dual limit to protect the cornea are relevant: firstly the aperture stop diameter of 7 mm permitting high irradiances for small beam diameters (noting that reducing the aperture stop in a revision of IEC 60825-1 has no impact, as long as the beam is smaller than the aperture since the limit is given as "power through aperture"). Secondly, while the injury thresholds decrease by a factor of 10 between 1300 nm and 1400 nm, the Class 3B AELs remain constant. Thus, in future editions of IEC 60825-1 it appears necessary to at least lower the limit for wavelengths between roughly 1300 nm and 1400 nm as well as to reduce the aperture stop diameter. In order to avoid an over-restrictive limit for shorter wavelengths, the wavelength dependence of the injury thresholds can be accounted for, for instance as done in the ANSI Z136.1-2014 limits. As an interim dual limit, the skin MPE lends itself to serve also for limiting the AEL of Class 1 laser products. The skin MPE is even "over"-restrictive for wavelengths less than 1300 nm. It might not be ideal that exposure at the skin MPE for the case of wavelengths close to 1400 nm might induce pain and aversion responses when the product is Class 1, but the skin MPE should be sufficient to prevent injuries, based on normal eye movements and aversion responses. The skin MPE can also be expressed as a limit that is to be compared against a "power through aperture" level, as is common for the classification of products. Multiplication of the skin MPE with the area of the exposure-duration dependent averaging aperture results in:

For $t < 10^{-9}$ s: $7.9 \times 10^{5}$ W
*Aperture stop diameter: 1 mm*

For $10^{-9}$ s $\leq t < 10^{-7}$ s: $7.9 \times 10^{-4}$ J
*Aperture stop diameter: 1 mm*

For $10^{-7}$ s $\leq t < 0.35$ s: $4.3 \times 10^{-2}\, t^{0.25}$ J
*Aperture stop diameter: 1 mm*

For $t \geq 0.35$ s: 0.1 W
*Ap. stop diam.: 0.35 s $\leq t <$ 10 s: 1.5 $t^{3/8}$; $t \geq$ 10 s: 3.5 mm*

When the measurement of the accessible emission is then performed with the corresponding aperture stop, the analysis is identical to determining the irradiance or radiant exposure averaged over the aperture stop and comparison against the skin MPE given as irradiance or radiant exposure. We note that for exposure durations exceeding 0.35 s, the increase of the area of the aperture with $t$ compensates for the decrease of the MPE specified as irradiance, resulting in a constant "power-MPE" of 100 mW. For the case of large homogenous beam profiles it is justified to perform the transformation of the irradiance-MPE into a power-MPE with a larger aperture. For instance, if the beam is homogenous and larger than 7 mm in diameter, a 7 mm aperture (factor 4 larger area as compared to 3.5 mm) can be used and the skin power-MPE for exposure durations above 0.35 s is then equal to 400 mW (to be compared to the power passing through a 7 mm aperture). We see that for large beam diameters, the Class 3B AEL of 500 mW (accessible emission measured through a 7 mm aperture) is close to the skin MPE and affords a comparable degree of safety. It is only for small beam diameters where the Class 3B limit permits irradiance levels at the cornea which for wavelengths in the regime where absorption becomes relevant, is not sufficiently protective.

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