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COMPUTER MODEL RESULTS ON THE WAVELENGTH DEPENDENCE FOR RETINAL THERMAL INJURY IN THE VISIBLE REGIME

Paper #P100

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Abstract

In the visible wavelength range, the current laser safety MPEs to protect the retina issued by ANSI Z136.1, IEC 60825-1 and ICNIRP are constant, i.e. do not feature a wavelength dependence. It has been shown before by David Jack Lund in the pulsed regime that a wavelength dependence exists and can be theoretically supported by the pre-retinal absorption factors as well as the absorption in the RPE as function of wavelength. However, we show in this paper that the transmission/absorption-based wavelength dependence only applies to short pulses, where heat flow does not play a role. Computer modelling shows that the longer the exposure duration becomes, the flatter the wavelength dependence becomes, so that for the cw case the constant MPE in the visible wavelength range is an appropriate trend that is not unduly over-restrictive. For the pulsed regime, a constant wavelength dependence might be over-restrictive in the red wavelength range, but has the advantage of being simple.

Also, raising MPEs has to be done with care in order to sustain a sufficient safety margin, while lowering the MPEs should only be done when the current MPEs were found to be associated to a safety margin that is too small. The data is also relevant for an ongoing revision of the international safety standard for ophthalmic instruments, ISO 15004-2 and the USA standard for ophthalmic instruments, ANSI Z80.36.

Introduction

In the visible wavelength range, in current safety standards, dual limits are defined to protect on the one hand against thermally induced injury of the retina and on the other hand against photochemically induced injury of the retina. In this paper, we discuss thermally induced injury, the respective exposure limits (MPE) and the corresponding limits for classification, the AEL of Class 1.

Laser safety limits are given in IEC 60825-1, ANSI Z136.1 as well as ICNIRP [1,2,3]. For laser safety limits, the wavelength dependence of the retinal thermal limits in the wavelength range of 400 nm to 1400 nm are accounted for by correction factors as part of the limits: C_A to express the wavelength-dependent absorption depth in the retina, and C_C to express the wavelength-dependent pre-retinal absorption in the eye (these are the symbols used in the ANSI and ICNIRP documents, IEC 60825-1 uses the symbols C_4 and C_7, respectively, but the values are identical).

For limits to protect against broadband incoherent radiation, the following documents are relevant: IEC 62471 [4], the ICNIRP broadband guidelines [5] as well as the photobiological safety standards for ophthalmic instruments, ISO 15004-2 and ANSI Z80.36 [6,7,8]. The concept for broadband radiation is to define spectral weighting functions that are applied to spectrally weight the exposure level that is compared against the limits [9]. That is, the wavelength dependence is contained and considered in the exposure level rather than in the limits. The exposure level is then also referred to as "effective" exposure. For the retinal thermal spectral weighting function, the symbol $R(\lambda)$ is usually used. As an example, the wavelength weighting to result in the thermally effective radiance L_R is obtained by weighting the spectral radiance $L_\lambda(\lambda)$:

$$L_R = \int_{380nm}^{1400nm} L_\lambda(\lambda) \cdot R(\lambda)\, d\lambda$$

This concept lends itself better for broadband radiation, but is otherwise equivalent to the correction factors for laser radiation in the limits, where the spectral weighting function R is equivalent (in many wavelength ranges, identical) to the inverse of the limit-correction factors (see for instance also discussion in [10]):

$$R(\lambda) \Leftrightarrow \frac{1}{C_A \cdot C_C}$$

In the visible wavelength range of 400 nm to 700 nm, the laser safety exposure limits and AEL for Class 1 are in all laser safety standards (IEC 60825-1, ANSI Z136.1 as well as the ICNIRP laser guidelines) constant, i.e. do not feature a wavelength dependence. Similarly, for photobiological safety standards for broadband incoherent radiation, for the wavelength range less than 700 nm, the spectral weighting functions for the retinal thermal hazard is equal to or less than 1 (less than 1 in the blue wavelength range), i.e. in IEC 62471, the ICNIRP broadband guidelines [4,5] as well as in

ISO 15004-2 and ANSI Z80.36-2016 [6,7]. However, in the 2021 revision of ANSI Z80.36-2021 [8], a wavelength dependence of the thermal hazard weighting function was introduced also in the visible wavelength range, where the value of 1 was kept for 700 nm, but the values in the visible wavelength range are significantly above 1, for instance 2.11 for the wavelength of 530 nm. This means that for white light sources such as operating microscopes, the emission level that is compared against the emission limit for Group 1 and Group 2 instruments is correspondingly increased. For typical white LED, the increase of the effective (weighted) emission level is of the order of at least 2. In the 2021 revision of ANSI Z80.36, the Group 2 continuous wave (cw) limit for the retinal thermal hazard was not increased. This means that products such as operating microscopes that were not far below the 2016 limits, and that were compliant with ANSI Z80.36-2016, (and were used regularly for many years for operations), are no longer compliant based on ANSI Z80.36-2021. The data presented in this paper will raise the question if the introduction of the strong wavelength dependence for the thermal hazard weighting function in ANSI Z80.36-2021 was justified for cw emission.

There was also a discussion for ANSI Z136.1 if the wavelength dependence in the visible wavelength range should be accounted for in a future revision of the standard.

In this paper we will limit the discussion to the *relative* wavelength dependence of retinal thermal injury thresholds predicted by a validated computer model [11], and how this wavelength dependence varies with exposure duration. A discussion of the *absolute* level of injury threshold as function of exposure duration and wavelength, and the margin relative to the current or potential future limits in the varying standards is not in the scope of this paper.

Predicted Relative Injury Thresholds

Figure 1 shows the injury thresholds for retinal thermal injury as function of wavelength, for a nominal retinal image diameter (gauss profile, 1/e diameter) of 25 µm, equivalent to an angular subtense of the apparent source of α = 1.5 mrad. Although the computer model is limited to thermally induced injury and predictions for micro-cavity induced injury are not included, the computer model results for 10 µs exposure duration are shown. When relative values are shown further below, we will include data for 1 µs exposure duration, based on the thermal model. This data is included to study potential trends with exposure duration, but it has to be noted that micro-cavity induced injury thresholds could well be lower than the predicted bulk-thermal thresholds.

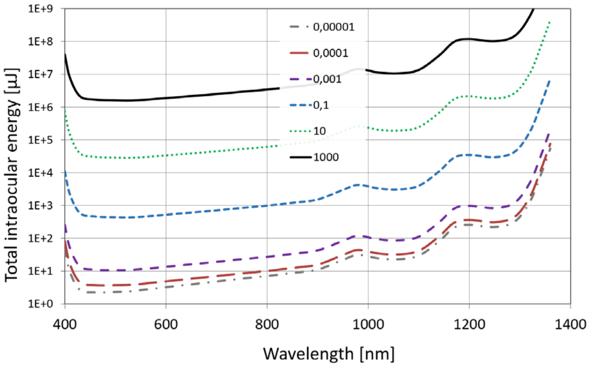

Figure 1. Computer model threshold data for α = 1.5 mrad as function of wavelength. The legend shows the exposure duration in seconds.

The basic nature of the wavelength dependence is well known and has already been characterized and discussed in the regime up to 100 ms by David Jack Lund [12,13]. In his work, the term "action spectrum" was used for the wavelength dependence. The theoretical action spectrum was based on the absorption spectrum of the retina as well as the pre-retinal spectral transmissivity.

In plots such as in Figure 1, it is difficult to discern differences of the wavelength dependence as the exposure duration varies. These differences are seen better when the injury thresholds from Figure 1 are normalized, as shown in Figure 2. We have chosen to normalize the data at 700 nm, which is also where the correction factor C_A and R(λ) is equal to 1. To see the variations in the visible wavelength better, the plot shows data only up to wavelengths of 900 nm.

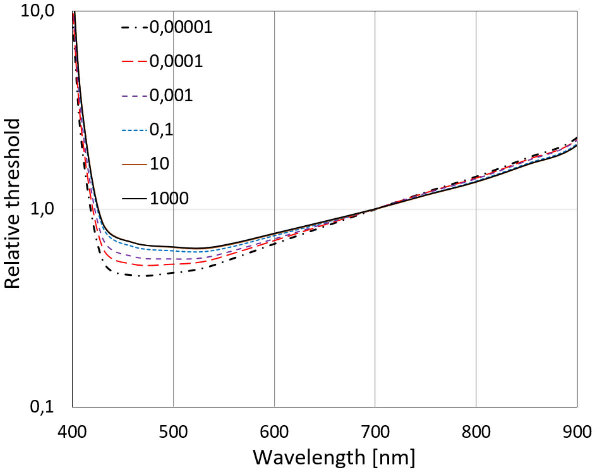

Figure 2. The threshold data of Figure 1 shown normalized to 700 nm, up to a wavelength of 900 nm.

The presentation in Figure 1 and Figure 2 is in terms of injury threshold. This can be compared against the wavelength dependence of C_A and C_C. To discuss the variation of the wavelength dependence with exposure duration, we prefer to use the inverse of the data, as shown in Figure 3. This presentation is equivalent to the concept of the spectral weighting functions for broadband limits. We note that for broadband limits, the same spectral weighting function applies irrespective of the exposure duration, which is part of the challenge when the wavelength dependence in the visible part is to be considered.

Again, the data was normalized to be equal to 1 at a wavelength of 700 nm. This is also the anchor point chosen in ANSI Z80.36-2021. We have chosen the term "Threshold weighting function" to use a term similar to the "hazard weighting function" used in the broadband limit documents.

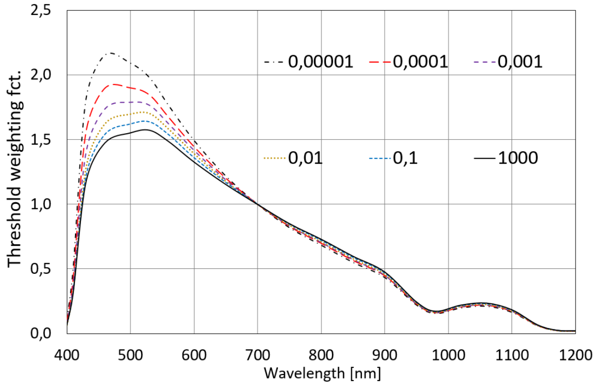

Figure 3. The inverse of the relative injury thresholds plotted in the figures above. This data-set is for α = 1.5 mrad. The legend is the exposure duration in seconds.

When the data is plotted in this "inverse" way, they can be directly compared with the hazard weighting functions of broadband limits. Also, in terms of understanding, we can see that the computer model predicts that radiation in the blue-green wavelength range has the maximum "effectiveness" to induce injury to the retina thermally. For instance, when the threshold weighting function has a value of 1.5 for a wavelength of 560 nm and an exposure duration of 1000 s, this means that the injury threshold is a factor of 1.5 lower than for 700 nm. We can also see the change of the wavelength dependence with exposure duration, although we note that for this data-set for α = 1.5 mrad, the threshold weighting function for 1000 s has a maximum of about 1.6 in the green wavelength range. For 10 µs, the maximum is shifted towards the blue and is equal to 2.2.

Figure 4. shows the threshold weighting function calculated for a top-hat retinal irradiance profile which subtends an angular subtense of α = 100 mrad. Here, exposure durations down to 1 µs were included.

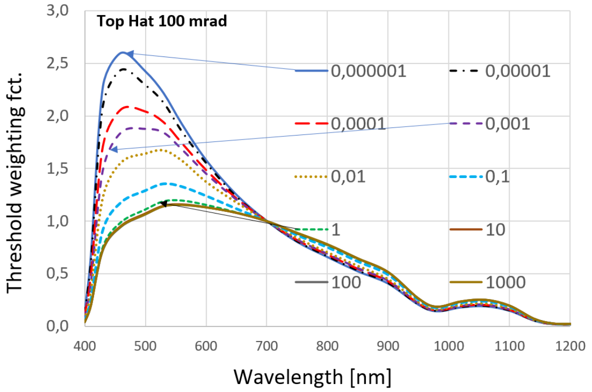

Figure 4. Threshold weighting functions calculated for a 100 mrad top-hat retinal irradiance profile. The curves for 10 s to 1000 s exposure duration lie on top of each other.

We note for α = 100 mrad compared to the earlier figures for α = 1.5 mrad, that the wavelength dependence variation with pulse duration is significantly pronounced. The curves for long exposure duration of 1 s to 1000 s have a maximum in the green wavelength range of 1.15, i.e. basically no wavelength dependence. The curves for very short pulses on the other hand, have a higher value than for 1.5 mrad, with a maximum of 2.4 for 10 µs and 2.6 for 1 µs exposure duration, respectively.

Thus, the wavelength dependence of the thresholds not only varies significantly with exposure duration, but the variation also depends on retinal image diameter. A direct comparison for α = 1.5 mrad and α = 100 mrad is shown in Figure 5.

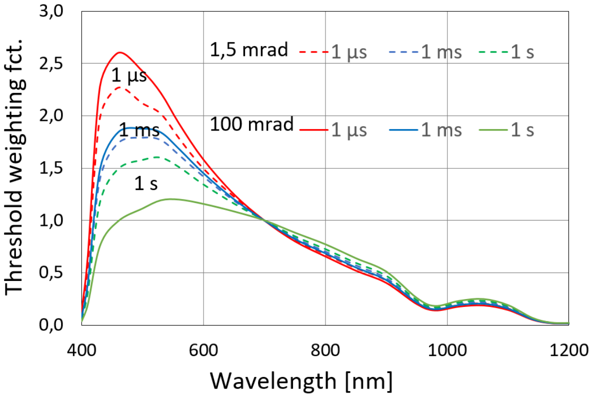

Figure 5. Comparison for selected exposure durations, α = 1.5 mrad and α = 100 mrad.

Comment on Biophysical Background

There is an apparent significant difference in the predicted wavelength dependence for various exposure durations. The predictions for very short pulses follow the theoretical "optical" wavelength dependence very well (see subsequent section). This "optical" wavelength dependence is based on retinal absorptivity and pre-retinal transmissivity, as already discussed by Jack Lund [12, 13]. The reason for the shallower (for large retinal image diameters, a basically non-existent wavelength dependence) for long exposure durations is that heat flow into the depth of the retina evens out differences in retinal absorption depth. For short exposure durations there is no time for heat flow during the exposure. The optical absorption depth (the inverse of the absorption coefficient) can be used as estimate for the depth of the absorbing volume. The incident radiation is absorbed in this volume and for a given irradiance at the retina, a larger absorbing volume results in a lower temperature rise. During short pulses, there is no heat flow out of this volume, and therefore the injury threshold as function of wavelength follows the spectral absorption depth. This direct relationship of optical absorption depth with injury threshold has been demonstrated very nicely for the cornea, based on injury thresholds in the nanosecond regime, as for instance discussed by Schulmeister et al. [14]. For longer exposure durations, heat flow into the depth of the tissue takes place. The longer the exposure duration, the deeper into the tissue the heat will flow and reduce the temperature in the absorbing volume. The distance *r* that heat travels (referred to as thermal diffusion length) in a given time *t* can be estimated by the thermal diffusivity *D* (such as of water) via:

$$r = \sqrt{D \cdot t}$$

When the thermal diffusion length is larger than the optical absorption depth (as a very rough concept), then heat flow evens the temperature profile out. In this regime, the temperature in the tissue is mostly given by the heat flow, which does not depend on optical properties.

This is well known for the cornea [15,16], where the laser MPE for wavelengths above 1400 nm feature a wavelength dependence that varies significantly with exposure duration. This variation reflects the wavelength dependence of the injury thresholds (Figure 6), which is very shallow for long exposure durations, and pronounced for short exposure durations.

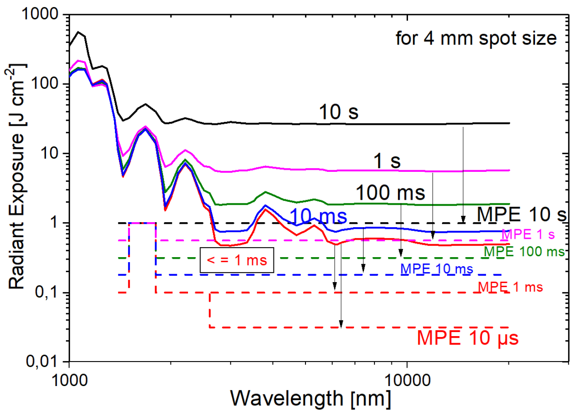

Figure 6. Computer model predictions for the cornea, compared to laser MPEs (adapted from [15]).

In the wavelength range above 1400 nm and for an exposure duration equal to 10 s, the exposure limit (MPE) for the cornea is constant. For an exposure duration of 10 µs, the MPE strongly depends on wavelength (reflecting the variation of the thresholds in a simplified way) and varies over a factor of 30 between the minimum and maximum.

This change of the wavelength dependence of the corneal MPE for different exposure durations would be equivalent to a change of the hazard weighting function depending on the exposure duration (where the hazard weighting function expresses the inverse of the wavelength dependence of the MPE, i.e. where laser MPEs are high, the hazard weighting function would be low). However, in the simplified concept of limits for optical broadband radiation, a variation of the hazard weighting function with exposure duration was so far avoided. The notion seems to be that "any dependence on exposure duration *t* has to be in the limits, not in the hazard weighting function".

Unfortunately, the thermal hazard function in the wavelength range of blue and green cannot be verified experimentally for long exposure durations, because the tissue is damaged photochemically at lower radiant exposure values [17].

Draft for ISO 15004-2

While ANSI Z80.36-2021 only features the thermal retinal hazard function for the aphakic eye (and our computer model is currently not set up for aphakic eyes), a 2021 committee draft of a potential update of ISO 15004-2 featured hazard functions both for aphakic and phakic eyes. The proposed draft is shown in Figure 7, compared with data from our model calculated for α = 100 mrad. Large retinal images (100 mrad is equivalent to 1.7 mm diameter on the retina) are typical for ophthalmic microscopes such as operating microscopes. Thus, to compare the data for α = 100 mrad seems appropriate.

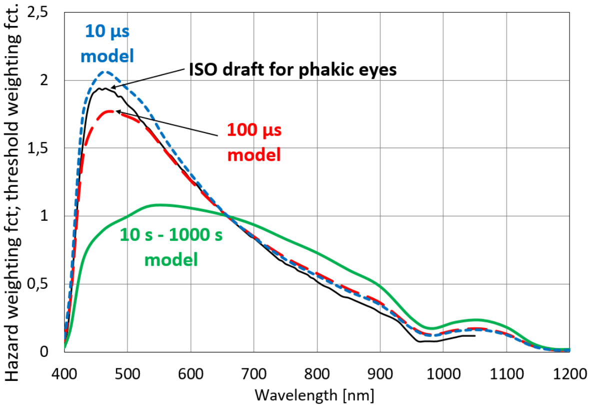

Figure 7. Retinal thermal hazard weighting function for phakic eyes from the committee draft for an update of ISO 15004-2 compared to predictions from our computer model for α = 100 mrad.

The thermal hazard weighting function of the ISO draft was apparently derived from optical absorption and transmission data of the human eye, not from actual injury thresholds (which is biophysically not possible for long exposure durations, see above). The proposed hazard function from the ISO draft can be fitted well by our model for pulse durations somewhere between 10 µs and 100 µs. However, our model predicts that for exposure durations of 10 s – 1000 s (with identical threshold weighting function for exposure durations above 10 s), the wavelength dependence is much shallower. This exposure duration regime (5000 s) is the basis for Group 2 instruments with cw emission. Thus, it seems that the proposed hazard function is appropriate for short pulses, but appears to be significantly over-restrictive for the cw emission regime.

Summary and Conclusions

Computer model calculations show that the degree of wavelength dependence of the retinal thermal injury thresholds in the visible wavelength range strongly depends on exposure duration. Only for short pulses are wavelength dependencies predicted that follow the “optical” wavelength dependence based on retinal absorptivity and pre-retinal transmissivity. For longer exposure durations, the computer model shows that heat flow evens out the “optical” wavelength dependence. This is well known and understood for corneal injury thresholds and reflected in the laser MPEs for the cornea, where for wavelength above 1400 nm, the wavelength dependence of the limits strongly varies with exposure duration. For exposure durations of 10 s and above, the corneal limits have no wavelength dependence.

The reasoning for the retinal thermal limits is similar, although somewhat more complex, because of the strongly different degree of pigmentation of the retinal pigment epithelium vs. of the choroid.

With the exception of ANSI Z80.36-2021, limits to protect the retina for thermally induced injury are constant in the visible wavelength range below 700 nm (or somewhat less restrictive in the blue wavelength range). This seems to be appropriate, and not over-restrictive, for exposure durations in the cw regime. For short exposure durations, when the safety limits are anchored to injury thresholds in the blue-green wavelength range, the constant wavelength dependence of the limits is somewhat over-restrictive for radiation in the red wavelength range.

When the introduction of the wavelength dependence in the visible would lead to lower safety limits, then this seems to be justified only when the present limits were unduly high, which for the green wavelength range is not the case. Therefore, it seems that to keep the wavelength dependence in the visible wavelength range constant for all exposure durations is the simple, and for cw emission also the appropriate approach.

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