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MODELLING OF THE LASER SPOT SIZE DEPENDENCE OF RETINAL THERMAL DAMAGE

Paper #105

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Abstract

Thermal damage models were used to calculate the damage threshold for retinal exposure as a function of retinal spot size diameter for pulse durations from 1 microsecond to 1 second. The calculated threshold data show that for short pulses in the thermal confinement regime, as expected from physical principals, the threshold exposure in terms of retinal radiant exposure does not depend on the diameter of the spot size. It is only for longer pulse durations that there are two regimes where for retinal spot sizes smaller than a certain 'breakpoint' (that depends on the pulse duration), the damage threshold depends on the spot size in a linear manner (dependence on "α" in terms of MPEs), and for spots larger than the breakpoint diameter, the threshold in terms or retinal radiant exposure again does not depend on the spot size. However, the current ICNIRP, ANSI and IEC exposure limit values assume an "α" dependence between 1.5 mrad and 100 mrad for all pulse durations, thus, for large spots grossly overestimating the risk for thermal retinal damage. Since the breakpoint that was identified in this study is equivalent in function and meaning to the definition of "α_{max}" a more accurate representation of the retinal thermal hazard can be achieved by defining a time dependent value of α_{max}.

1. Introduction

Current laser exposure limit guidelines and standards (ICNIRP [1,2], IEC 60825-1 [3] and ANSI Z136.1 [4]) define the retinal spot size dependence of the maximum permissible exposure (MPE) values for thermal damage of the retina in terms of a multiplication factor in the MPEs, that varies the values of the MPE relative to the MPE value for the assumed minimal retinal spot size. For minimal spot sizes the MPE is also the smallest and the factor (C_6 for IEC and C_E for ICNIRP and ANSI) equals unity.

1.1 Corneal and retinal 'space'

The MPE values as such are specified at the cornea, i.e. exposure levels (radiant exposure or irradiance) at the cornea (averaged over the area of a 7 mm aperture) are compared to the MPE value, which is either given in units of J m^{-2} or W m^{-2} [5]. By multiplying the average radiant exposure at the cornea with the area of the 7 mm aperture, a value in terms of energy (or power) is obtained, which is equivalent to what in experimental threshold studies is referred to as the 'total intraocular energy', TIE. When the MPE is also multiplied with the area of the 7 mm aperture, a comparison of this value (now given in Joules or Watts) with the TIE is equivalent to comparing the averaged radiant exposure with the MPE. The energy per pulse that is incident on the retina can be calculated by multiplying the TIE with the transmittance of the ocular media in front of the retina. The retinal radiant exposure in units of J m^{-2} can be calculated from this value by division with the area over which the incident energy is distributed. In this discussion, for simplicity, we assume a top hat irradiance profile on the retina; see [6] for a discussion on non-top hat retinal distributions.

The dependence of the MPE on the retinal spot size is given in terms of 'the angular subtense of the apparent source' (symbol: α) which characterises the angle that the retinal irradiance pattern subtends at the corresponding principle plane of the cornea-lens system of the eye (see [7] in these proceedings for a more detailed discussion on the apparent source). For a human, the retinal spot diameter d_r in units of μm is related to the angular subtense of the spot α in units of mrad by $d_r = \alpha$ 17 mm, where the air-equivalent distance from the retina to the corresponding principle plane of the human eye is used. Thus the area of the retinal spot is directly proportional to α^2 and the retinal radiant exposure is directly proportional to TIE/ α^2.

With these relationships it is possible to discuss the spot size dependence (as a function of retinal spot diameter and pulse duration) of the retinal thermal damage either in 'retinal space', i.e. by analysing the damage threshold in terms of retinal radiant exposure (with units of J m^{-2}) or in 'corneal space' where the threshold for retinal damage is specified in terms of the TIE (with units of J or μJ).

1.2 Current dependence on retinal spot size (α)

The angular subtense that characterises the smallest spot size that can be optically achieved at the retina is referred to as the *'minimum angular subtense'* and has the symbol α_{min} and the numerical value of 1.5 mrad, i.e. α_{min} = 1.5 mrad. The minimum angular subtense α_{min} characterises the minimum retinal spot size that can be obtained, i.e. even if the source (the 'object' that emits the radiation in the optical sense) would itself be characterised by an angular subtense of less than 1.5 mrad. There is also a *'maximum angular subtense'* with the symbol α_{max} and the numerical value of 100 mrad, i.e. α_{max} = 100 mrad. In contrast to α_{min}, the maximum angular subtense of 100 mrad (equivalent to angle in degrees of 5.7°) does not reflect an actual optical limitation of the retinal image size, but rather characterises a break-point in the dependence of the retinal thermal hazard on the diameter of the retinal spot size, as will be discussed further below.

The retinal thermal MPE values depend on the angular subtense of the apparent source by way of the factor C_6 (or C_E in ANSI and ICNIRP documents), which is defined as

$$C_6 = \frac{\alpha}{\alpha_{min}} = \frac{\alpha}{1.5\,mrad}$$

where α is given in units of mrad and is limited to values between α_{min} and α_{max}. If the actual angular subtense of the apparent source is less than 1.5 mrad, the value of 1.5 mrad is assigned to α; if it is larger than 100 mrad, the value of 100 mrad is assigned to α. For sources larger than 100 mrad it is important to note that the angle of acceptance for determination of the exposure level that has to be compared to the MPE value must also be limited to 100 mrad. It is pointed out that the specification of C_E in the ICNIRP guidelines and in Table 6 of the current version of the ANSI laser safety standard can be misinterpreted to mean that α is not limited to 100 mrad and C_E can increase beyond 66.6, even though the measurement angle of acceptance (also referred to as limiting cone angle) is limited to 100 mrad. Limiting the angle of acceptance to 100 mrad and limiting α to α_{max} = 100 mrad, for a top-hat retinal irradiance profile is equivalent to assess the exposure level with an open field of view and to determine the factor C_6 (or rather C_6^{open}) by [5]

$$C_6^{open} = 66.6\,\frac{\alpha^2}{\alpha_{max}^2} = \frac{\alpha_{max}}{\alpha_{min}}\frac{\alpha^2}{\alpha_{max}^2} = \frac{\alpha^2}{\alpha_{min}\,\alpha_{max}}$$

when α is larger than α_{max} (i.e. in this case the vale of α is no longer limited to 100 mrad). That is, when the MPE is determined with C_6^{open}, the angle of acceptance of the measurement shall not limit the exposure assessment and the total energy that passes through the 7 mm aperture is relevant in the comparison with the MPE, which makes it the superior representation in the discussion of the spot size dependence and for the comparison to experimental threshold values which are given in terms of TIE (i.e. not limited by an angle of acceptance of γ = 100 mrad).

The general dependency of the exposure limits when expressed in terms of corneal space (i.e. the usual MPE representation) and in terms of retinal radiant exposure are shown in figure 1a and 1b, respectively (values for pulse durations between 1 ns and 18 μs for visible radiation).

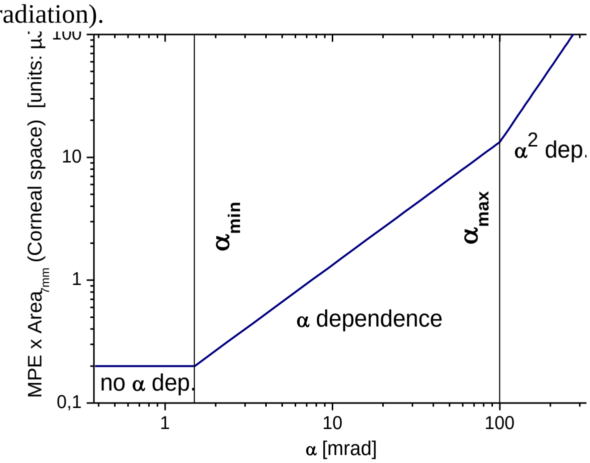

Fig. 1a General dependence of the current MPE values (which are specified as corneal levels) as function of α.

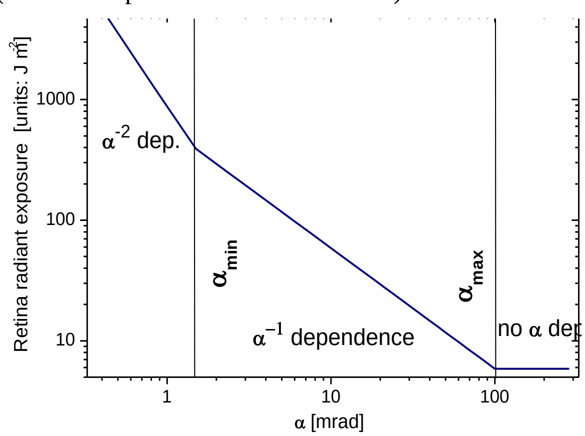

Fig. 1b General dependence of the current MPE values when specified as retinal radiant exposure as function of α, assuming ocular transmittance of 1.

2. Methods - Thermal Damage Models

Two retinal thermal damage models were realised, one based on a an explicit finite difference method to model heat flow and calculate temperature increases per time-step and per spatial grid, and a second one which is based on an analytical solution of the heat flow equation for melanosomes which are modelled as spheres and this model is generally referred to as 'Thompson – Gerstman' Model [8].

Both models are based on the heat flow equation but differ in the spatial definition of the absorption of the radiant energy. The finite difference model assumes absorption following Beers exponential law in homogeneous retinal pigment epithelium (RPE) and choroid layers and solves the heat flow equation numerically. The Thompson-Gerstman model assumes absorption only within the discrete melanosome particles in the RPE. Temperature fields produced by the individual melanosomes are superimposed to produce the temperature distribution in the retina as a function of time.

The calculations are based on specification of the radiant exposure profile that is incident on the retina, or more specifically, on the RPE. The RPE is modelled with a thickness of 15 μm, the thermal properties for all media are those of water. To reduce calculation time, Dirichlet boundary conditions were used in the finite difference model which produced equivalent results to using a larger modelling space.

The absorption coefficient for the RPE for the finite difference model was set to 500 cm^{-1} for the calculations shown in this paper, which is the value that can be derived for a wavelength of 600 nm from the data by Maher [9] and for a wavelength of 695 nm from the data by Gabel [10]. The absorption coefficient of the choroid was set to 100 cm^{-1}. Rectangular temporal pulse shapes and top-hat retinal profiles were used in this analysis (see [6] for other retinal profiles). When the finite difference model was changed to assume a constant radiant exposure over the whole RPE and the absorption coefficient for the finite difference model set to 70 cm^{-1}, the temperatures that were produced by the two models where practically identical after a modelling duration of about 10 μs, when the hot-spots around the melanosomes had been averaged out by heat diffusion.

Both models employ the Arrhenius integral of the absolute temperature as a function of time to predict denaturization of tissue leading to damage. For the two Arrhenius integral parameters, the numerical values given by Takata [9] were used. For a given pulse duration and retinal spot size, the total energy incident on the retina was varied to find the value which produced a 20 μm diameter area where the damage integral in the central plane of the RPE was equal or greater than unity.

Retinal injury thresholds were computed for a number of retinal irradiance diameters ranging from 30 μm to 2000 μm for each of several exposure durations from 1 μs to 1 s.

3. Results - Calculated Thermal Damage Thresholds

The calculated retinal radiant exposure damage thresholds as a function or retinal spot size for pulse durations from 1 μs to 1 s are shown in figure 2. Retinal spot sizes varied from 30 μm to 2 mm.

Two regions can be clearly distinguished, where the logarithmic slopes of the curves (threshold as function of α) are -1, i.e. a $1/\alpha$ dependence, and another one where the thresholds do not depend on α, i.e. a logarithmic slope of 0. These two regions are separated by a 'knee' in the curve, which can be approximated by a breakpoint when straight lines (in logarithmic coordinates) are fitted to the left and to the right part of the curves, as shown in figure 3. The position of the breakpoint depends on the pulse duration: for pulse durations less than 20 μs, within the range of spot sizes of between 30 μm to 2 mm, there is no breakpoint discernible and the thresholds all have the same value irrespective of the spot diameter, while for long exposure durations, a breakpoint can be identified that shifts in position depending on the pulse duration. The dependence of the threshold on spot size diameter 'left' of the knee for pulse durations longer than about 20 ms according to the model is not exactly α^{-1} but rather $\alpha^{-1.1}$. This dependence reduces to 'no-α dependence' for short pulses (< 20 μs) as the knee is moving out of the modelling range (and the dependence would be different for the regime where the image size is limited by scattering and potential other effects to a minimum size, which according to the present standard would be for spot diameters less than 25 μm). Figure 4 shows the breakpoint as function of pulse duration.

The threshold data can also be plotted as function of pulse durations for a given spot size and this is shown in figure 5. The dependence of the threshold as function of pulse duration for pulse durations longer than approximately 1 ms can be fitted well with a straight line in log-space and equals $t^{0.9}$ for small spots and $t^{0.41}$ for large spots.

The data plotted in terms of corneal space is shown in figure 6, where the transmittance of the eye is taken as 1.

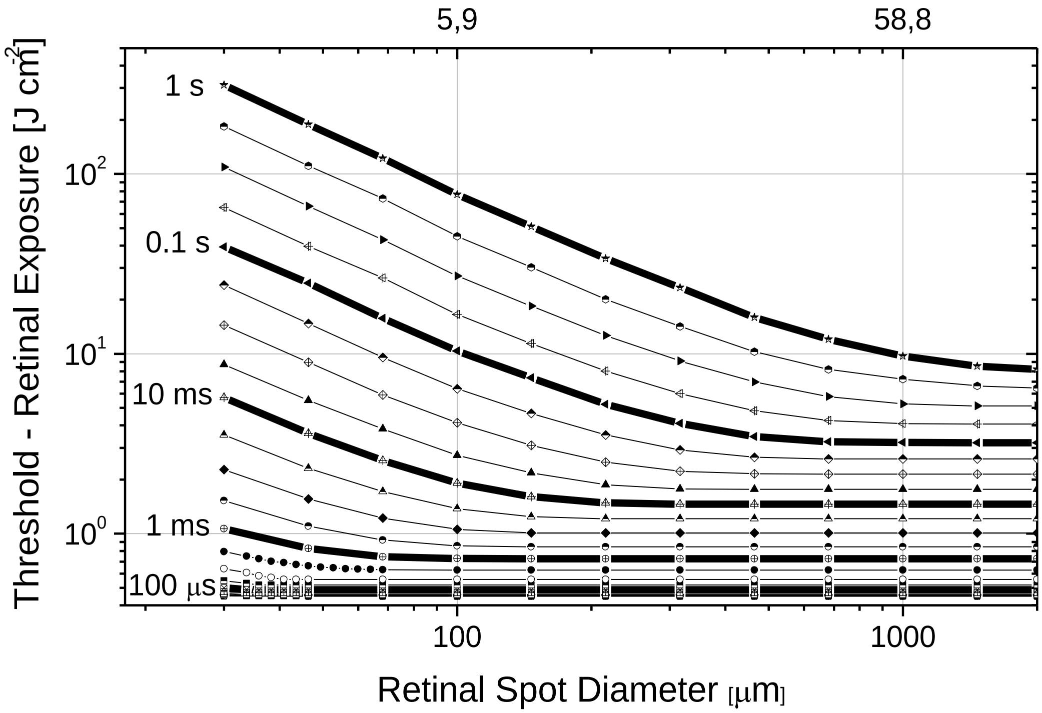

Figure 2. Calculated retinal threshold values as function of retinal spot size diameter for a range of pulse durations between 1 μs and 1 s. The thresholds are expressed as retinal radiant exposure.

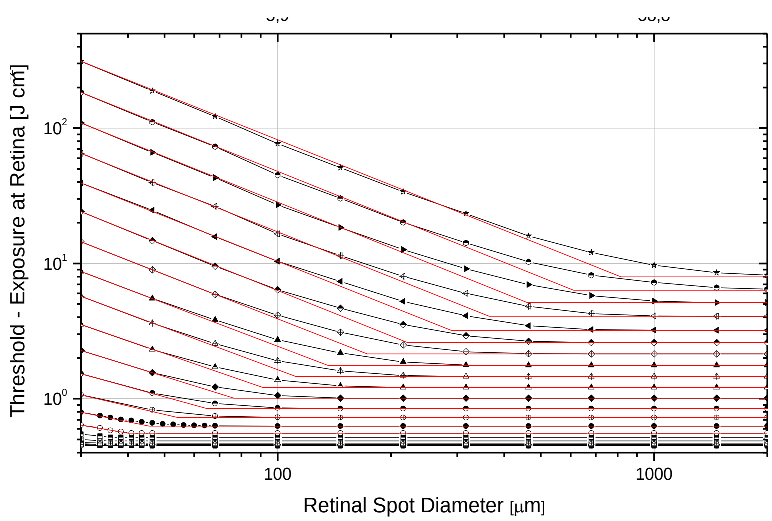

Figure 3. By fitting straight lines to the threshold data in log-space, the position of the breakpoint between the α^{-1} and the α^{0} region of spot size dependence is defined.

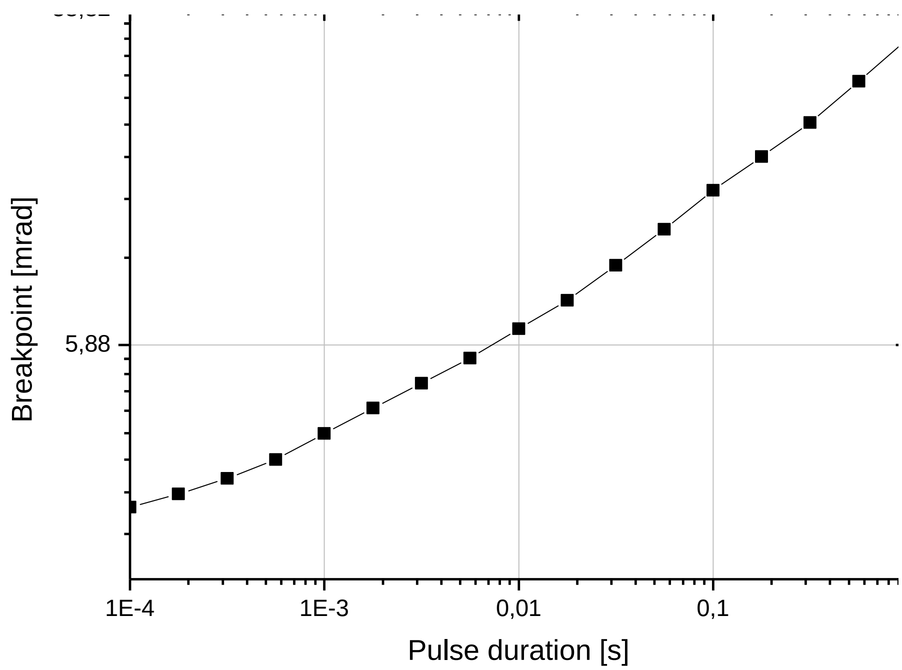

Figure 4. Position of the breakpoint (as found according to figure 3) as a function of pulse duration. No breakpoint is discernible for pulse durations less than approximately 20 µs and the breakpoint can be set to 1.5 mrad for this pulse duration value (the value which is shown above in the plot for 100 µs equals 2 mrad).

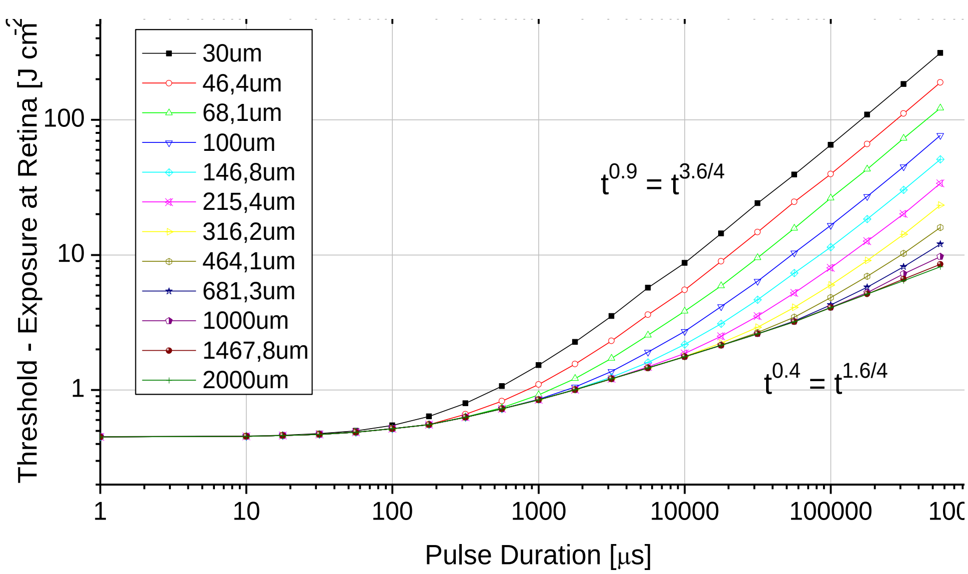

Figure 5 The retinal threshold data plotted as function of pulse duration for spot size diameters between 30 µm and 2 mm.

4 Discussion

4.1 Comparison with experimental data

The calculated thresholds compare favourably with reported experimental data for rhesus monkey eyes in terms of spot size dependence and pulse duration dependence for pulse durations between 1 ms and 1 s, as shown in Table 1.

For the data presented in this paper, the absorption coefficient of the RPE was not varied to model the wavelength dependence of this parameter. The absorptivity of the RPE generally decreases with increasing wavelength, i.e. the radiation is strongly absorbed in the blue and green part of the spectrum, while near infrared radiation penetrates well into the choroid. For the heavy pigmented retina of a monkey eye, the value of 500 cm^{-1} as used for the present calculations seems to be representative of red wavelengths [9], or according to the data presented in [11], where the monkey RPE is modelled with a thickness of 12 µm, of near infrared wavelengths of around 950 nm. However, it also needs to be considered that the RPE thickness in our calculations was set as 15 µm which produces higher levels of energy absorbed in the RPE. While the threshold values calculated with the Thompson-Gerstman model vary linearly with the absorption coefficient of the model-melanosome, this is not the case for the finite difference model when the exponential Beer law of absorption is used, and consequently the threshold data can not be linearly adjusted with varying absorption coefficient. However, not only the absorption coefficients of the RPE and choroid exhibit a certain wavelength dependence, so does also the transmittance T of the ocular media in front of the RPE. This value is relevant for a comparison with animal study data, which are given in terms of TIE. Data from Maher [12] indicate values of 0.54 for a wavelength of 500 nm to 0.67 for a wavelength of 700 nm and the calculated retinal threshold data as shown above in the figures was consequently multiplied by a factor of between 1.9 and 1.5 for comparison with the values reported as TIE for the monkey eye. The multiplication factor in Table 1 is a multiplication factor which was chosen to approximately minimize the difference between the model data and a given set of experimental values. This multiplication factor, for the model data presented here, also includes the influence of the dependence of the absorption coefficient of the RPE on the calculated threshold.

Table 1. Comparison of available experimental threshold data with calculated thresholds. The criteria for selection of the experimental data were: wavelength range between 400 nm to 700 nm, pulse duration between 1 ms and 1 s, rhesus monkey eyes, minimum of three data points for different spot sizes.

Author, reference	Mult Factor	Wavelength	Pulse dur.	Spot size range (number of data points within that range)	Range of relative difference
Beatrice [15]	0.8	514 nm	1 s	50 – 598 µm (3)	0.98 – 1.04
Ham [16]	1.6	633 nm	250 ms	50 – 211 µm (3)	0.7 – 1.1
			1 s	50 – 325 µm (4)	0.8 – 1.3
Allen [17]	0.8	694 nm	2 ms	135 - 1350 µm (4)	0.91 – 1.06
Allen [17]	2.0	400 - 900 nm Xenon arc lamp	4 ms	220 - 640 µm (3)	1.5 – 2.2
			10 ms	110 - 640 µm (4)	0.5 – 1.9
			20 ms	110 µm (1) 220 – 1300 µm (4)	0.5 0.8 – 1.2
			100 ms	110 µm (1) 220 – 1300 µm (4)	0.63 0.90 – 1.08

In the interpretation of the value of the multiplication factor as 'goodness of fit' of the calculated data in absolute terms, it needs to be considered that the experimental data is influenced by a number of factors [13,14] such as the region of the retina (macula or extra-macula – the macula is more highly pigmented and thus extra-macular thresholds are higher than thresholds determined in the macula) or the time of determination of the opthalmoscopically visible lesion (some studies used a 5 min endpoint such as for the Xenon arc lamp data, others 24 hours – the 24 hour thresholds are typically lower than the 5 min or 1 hour data). From each of these two factors, the experimental threshold data is typically affected by a factor of up to 2 and this would have an impact on the multiplication factor of table 1. Also it is noted that the temporal pulse profile will have an influence on the threshold; for the data presented in this paper, rectangular temporal pulse shapes were used, which should be a good representation of pulses for those studied that used cw sources and shutters to define the pulse duration. Also the retinal profile in experimental studies is often Gaussian and not top hat, as assumed in the calculations, which gives rise to a difference, depending on the pulse duration, of up to a factor of 1.4 [6].

Considering the range of pulse durations (3 orders of magnitude) and the range of spot sizes from 50 μm to 1300 μm (i.e. per study usually over a range of a factor of 10 from the smallest to the largest spot), the general trend in terms of spot size dependence for different pulse durations, as predicted by the thermal model, fits very well with the available experimental data. Once a corresponding multiplication factor is chosen for a given experimental study, the difference between the model and the experimental data is generally less than ± 30 %. The spot size dependence is particularly well predicted for the 514 nm, 1 s data by Beatrice where the difference is less than ± 4 % for three spot sizes between 50 μm and 600 μm, as well as for the data by Allen for 694 nm, 2 ms pulse duration and four spot sizes between 135 μm to 1350 μm and a relative difference of less than ± 9 %. Also most of the Xenon arc lamp data by Allen is very well described by the model calculations, with relative differences of less than ± 10 % for 100 ms pulses with spot sizes between 220 μm to 1300 μm. The absolute values of the modelled threshold data, and therefore the multiplication factor, depend on wavelength dependent absorption of the radiation in the RPE as well as on specified endpoints of the study (time of examination after exposure, macula or extra-macula) as well as the influence of temporal pulse shape and spatial retinal irradiance profile. These factors have to be studied in more detail by further modelling and analysis of the original publications. The multiplication factor values reported in Table 1 fall well within the range which can be expected for these kinds of variabilities.

The model, however, fails to predict the reported spot size dependence for pulses in the microsecond and nanosecond regime. In references [15], and [18] to [21], the dependence of retinal thresholds as function of spot size are given for five different pulse durations from 7 ns to 3 μs. For all of these reports, the model produces thresholds that are a factor of at least 10 too high, i.e. the experimental thresholds are much lower as predicted by the finite difference and Thompson-Gerstman thermal model. This can be explained by the production of bubbles around the melanosomes which is well studied for pulses in this pulse duration regime (see references in [8]). The formation of bubbles appears to reduce the threshold in comparison to a purely thermal denaturation. However, the experimental data also exhibit a spot size dependence which can not be explained on the basis of the thermal model. The α^{-1} dependence of the older data sets [15, 19, 20] is contrasted by the newer data sets of [21] which exhibit no spot size dependence of the retinal limits (as also predicted by the thermal model) for spot sizes larger than 70 μm. However, the threshold (in terms of retinal radiant exposure) in the newer study increases as the spot diameter decreases below 70 μm which is difficult to explain on the basis of the damage effect which for both thermal denaturation in the thermal confinement regime as well as bubble formation should only depend on the retinal radiant exposure and not on the size of the irradiated area (see [22] and [23] for a more detailed discussion). One possible reason for the observed spot size dependence for the spots with reported diameters of less than 70 μm is that the actual retinal spot diameter is larger than predicted from the beam that enters the eye, which might be due to scattering in the eye. An additional factor might also be that for these small spots, the discrete melanosome distribution within the RPE starts to play a role [13] (with an estimated melanosome density of about 200 per RPE cell, the average distance from one melanosome centre to the next is of the order of 5 μm).

4.2 Comparison with current MPE values

Current laser safety standards specify the same spot size dependence irrespective of pulse duration, as discussed in the introduction. It appears from the model data that this is an oversimplification leading to unnecessarily large safety factors between the MPE and the ED-50 value.

In terms of safety factor, there seems to be a sufficient ratio of the ED-50 value to the MPE for all pulse durations and spot sizes, with the potential exception of values for the green wavelength range with pulse durations between 1 ns and 10 ns and spot sizes of the order of 70 µm as reported by Zuclich et al. in [21]. The safety factor in this case could be increased by commencing the decrease of the MPE with pulse duration already at for instance 10 ns and not only at 1 ns, which is currently the case. For the case that scattering in the eye is confirmed to result in "thermally effective" spot sizes of not less than for instance 70 µm, α_{min} could be increased to about 5 mrad (with potential adjustment of the basic MPE value) which would also better reflect the spot size dependence of the 532 nm data reported for 7 ns pulse data [21]. However, for such a change to be proposed, further studies are necessary.

In terms of the variation of the general spot size dependence of the threshold for different pulse durations, however, the available model clearly indicates that the current specification by ICNIRP and ANSI is producing MPE values for pulse durations less than 1 s which are too conservative, i.e. unnecessarily low. This comes about since the basic MPE is specified for small sources which is then increased proportionally to α for intermediate sources by a factor C_E (or C_6 in the IEC standard) as described above, and only for sources larger than α_{max} = 100 mrad is the spot size dependence of the current MPEs in effect following an α^2 dependence. The model data (and experimental data as available) show that this dependence is only correct for long exposure durations of the order of several seconds, where the breakpoint between the α– and α^2-dependence when specifying the thresholds as TIE (compare Figures 1a and 1b) is of the order of 1.7 mm. For smaller pulse durations, the MPEs should actually follow the α^2 dependence starting at smaller spot sizes than 100 mrad. For pulse durations less than about 20 µs (which coincides well with the value of 18 µs which is the breakpoint in terms of dependence of the MPE on pulse duration), it appears that the α^2 dependence should be specified for all spot diameters above α_{min}. This could be relised by defining a pulse duration dependence of α_{max} similar to that shown in figure 4, which would result in an effective increase of the MPE of up to a factor of 66.66 (100 mrad /1.5 mrad) as shown in figure 6.

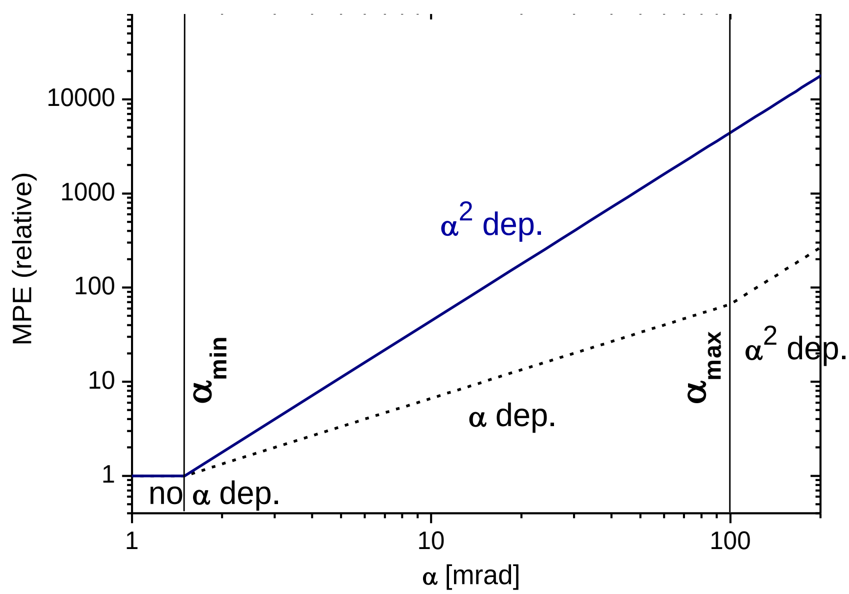

Figure 6. Impact of reducing α_{max} to be equal to α_{min} for pulse durations less than 18 µs on the retinal thermal MPEs. The dotted line shows the present spot size dependence, the full line shows the MPE value when α_{max} would be reduced to be equal to α_{min} for pulse duration less than 18 µs.

The dependence of the MPE values for pulse durations longer than 18 µs is given as $t^{0.75}$, i.e. $t^{3/4}$. The model data (figure 5) show a somewhat 'steeper' time dependence for small spots of $t^{0.9}$, i.e. $t^{3.6/4}$, while the exponent of the pulse duration dependence decreases to $t^{0.4}$, i.e. $t^{1.6/4}$ for large spots. The pulse duration dependence of $t^{0.75}$ for retinal thermal damage seems well established based on the assembly of experimental ED-50 as function of pulse duration (see for instance [8]). Further analysis of the available experimental data and of model calculations, for instance including the wavelength dependence of the absorptivity of the RPE, non-rectangular temporal pulse profiles and retinal exposure profiles (Gaussian or top-hat) is needed in this respect. However, it is interesting to note at this stage that the time dependence of corneal and skin MPE values that is specified as $t^{0.25}$ (i.e. $t^{1/4}$) is reflected also in the retinal model data for large spot sizes. This definition of the time dependence of the corneal and skin MPE can be retraced to experimental threshold values which were typically determined with spot diameters of 1 mm or above. If the spot size dependence of the retinal thermal MPEs were specified with a value of α_{max} that varies with pulse duration as shown in figure 4, the dependence of the MPE values on pulse duration for large spots would also be decreased to a value comparable to $t^{1/4}$.

5. Summary

Thermal damage models were used to calculate retinal threshold values for a wide range of retinal spot sizes and for pulse durations between 1 μs and 1 s. The models reliably predict spot size dependencies of experimental threshold values for non-human primates for pulse durations between 1 ms and 1 s. Based on the results of the model data and the experimental data, the current definition of the spot size dependence of the ICNIRP and ANSI thermal retinal damage MPE values are unnecessarily low for intermediate sources and pulse durations less than 1 s. The spot size dependence could be well described by a time dependent α_{max}, which increases from a value of 1.5 mrad for pulse durations less than 18 μs to a value of about 70 – 100 mrad for exposure durations of several seconds.

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