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Retinal thermal laser damage thresholds for different beam profiles and scanned exposure

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ABSTRACT

A computer model was used to predict thresholds for 532 nm scanned retinal exposure and exposure for different retinal beam profile geometries, including rectangles and ring shaped profiles. The image analysis method described in IEC 60825-1 Edition 1.2 – maximizing the ratio of power within a rectangle over the value of α for this rectangle – was applied to the different profiles to determine α and the fractional power that would be compared to the MPE value. The predicted thresholds for these special types of retinal exposure were compared with the predicted damage threshold for top hat profiles for the value of α that resulted from the image analysis method. The comparison shows that the most restrictive power/α ratio method produces appropriate results, provided that a time dependent α_{max} is used, as was proposed at BIOS 2006.

Key words: laser safety, ICNIRP, computer model, retinal thermal injury, threshold, MPE, IEC 60825-1, ANSI Z136.1

1. INTRODUCTION

Exposure limits for laser radiation are set on the international level by ICNIRP [1]. These exposure limits are adopted by IEC and published in IEC 60825-1 [2] and IEC 60825-14 [3], where the exposure limits are referred to as maximum permissible exposure, MPE. ANSI also sets MPEs for laser radiation in ANSI Z136.1 [4] on a US national basis; however, these are usually identical with ICNIRP ELs. The tables of MPEs in the above documents specify ELs that apply for retinal thermal injury and that are a function pulse duration, wavelength and the parameter α that is referred to as the "angular subtense of the apparent source" [5] (see Fig. 1). IEC 60825-1 and ANSI Z136.1 also list emission limits (Accessible Emission Limit, AEL) based on which laser products can be assigned laser safety classes. The AELs for the classes 1, 1M, 2, 2M and 3R are directly related to the MPEs by way of multiplication with the area of a specified aperture which for the retina has a diameter of 7 mm (see for instance Henderson and Schulmeister [6]). The MPEs are stated as radiant exposure or irradiance at the level of the cornea, while the AELs are stated as energy or power. Thus, the MPE values multiplied with the averaging aperture and therefore stated as energy are more directly comparable with retinal damage thresholds which are usually given as total intraocular energy (it is noted that these "energy MPEs" are numerical identical to the AEL values for Class 1 and Class 1M, however, to prevent misunderstandings about the concept of human exposure limits on one hand and product emission limits on the other, the term AEL should not be used in this context). Also for the purpose of this paper it is more convenient to use total intraocular energy and MPEs specified as energy.

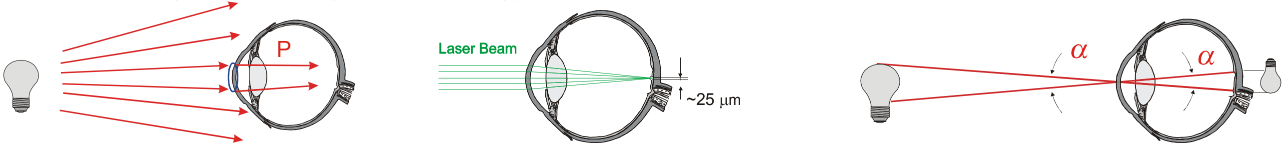

Figure 1. The power that enters the eye and the area over which it is spread on the retina are the two important factors to assess for a safety of optical radiation that can damage the retina.

The concept of the dependence on retinal spot size is that retinal thermal MPE (or the AEL values) is defined for a minimum angular subtense where $C_6 = 1$. This basic limit is then scaled with the parameter α to reflect the dependence

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of the damage threshold on the size and shape of the retinal profile. The parameter α is therefore to be seen as “thermal diameter” of a given retinal irradiance profile. Since only for a circular top-hat profile (constant irradiance profile) the diameter of the profile is actually well defined, we argue that the top-hat profile defines the baseline, i.e. a top-hat profile with a diameter of, for instance 100 µm also has an associated “thermal diameter” of 100 µm, with which α can be calculated with the defined air-equivalent length of the human eye of 1.7 mm: 100/1.7 = 58 mrad.

For other types of profiles, a method needs to be defined of how to determine α. Traditional beam diameter criteria that are used for non-safety purposes, such as the second moment criterion or the more simpler and therefore even less generally applicable criterion of the 1/e level or the 68 % energy level, are problematic when used to determine the parameter α (see the following paragraphs but also the example of application of the different beam diameter methods for ring shaped retinal irradiance patterns. In the new edition of IEC 60825-1 a method is described which can be called the „Most Restrictive Ratio“ (MRR) method and which is also discussed below.

In this paper, we apply the MRR method for rectangular and ring shaped retinal profiles for different pulse durations in the thermal damage regime for both the current constant value of α_{max} as well as a proposed time dependent value of α_{max}. Safety factors between the damage threshold determined with a computer model for a top hat profile and the respective MPE are compared with the safety factor for the actual profile.

We also present damage thresholds for scanned retinal exposure for which currently no guidance based on bioeffects studies is available.

1.1 Time dependent α_{max}

The spot size dependence study discussed in [7, 8] for circular top hat profiles showed that there is an unnecessarily large safety factor in the current MPEs for short pulses and extended sources. This large safety factors comes about because the damage threshold for short pulses of for instance 20 µs depends on the local radiant exposure irrespective of the actual image size, and for longer exposure durations the break between the current α dependence and the spot size region where the MPE no longer depends on α, depends on the pulse duration. This breakpoint is referred to in ANSI and IEC laser safety standards as α_{max}. To reduce needlessly large safety factors it was proposed by Schulmeister et al. [7] to use the following formula for the time dependence of α_{max}:

$\alpha_{max} = 200\ t^{0.5}$ (for 625 µs < t < 0.25 s)

where t is in seconds and α_{max} is in mrad. α_{max} equals 100 mrad for 0.25 s, and decreases to 5 mrad at 625 µs.

It was suggested to limit the decrease of α_{max} to 5 mrad, since decreasing the value of α_{max} to angular subtenses smaller than 5 mrad for short pulse durations would also amplify the amount by which the MPE for the nanosecond region would have to be lowered (where the safety factor for the spot size of 5 mrad is currently too small). To decrease α_{max} to a value of 1.5 mrad would make the evaluation of short pulsed sources closer to what would be expected on a biophysical basis since an image evaluation where both α_{min} and α_{max} are 1.5 mrad would mean that one would search with a field of view (evaluating area) of 1.5 mrad for the location in the image which maximizes the power within a 1.5 mrad area, which would be the same as looking for the maximum retinal irradiance point (averaged over 1.5 mrad). Setting the smallest α_{max} to 5 mrad rather than 1.5 mrad introduces an additional safety factor for extended sources and for pulses shorter than 625 µm.

We will see that the introduction of a time dependent α_{max} not only reduces the needlessly large safety factor for extended sources and short pulses, but is also necessary for meaningful results of the method discussed here to determine α for an arbitrary profile.

2. BEAM DIAMETER DEFINITIONS

2.1 ‘Traditional’ beam diameter definitions

Traditional beam diameter definitions are the diameter where the encircled energy has 63 % of the total power (this method is directly only applicable for circularly symmetric beam profiles) or the diameter where the local irradiance equals 1/e of the maximum irradiance value. For Gaussian beam profiles, these two are equal. The so called ‘second moment’ diameter (2M), which is standardized in ISO 11 146, has the distinct advantage that as long as the beam diameter for any (not only Gaussian) beam is determined and defined by the second moment technique, then simple beam propagation formalisms developed for beam propagation of Gaussian beams (such as the ABCD law) can be used. For a Gaussian beam profile this produces a 2M diameter which is identical to the $1/e^2$ diameter, however, for other profiles it deviates substantially from other diameter definitions. The most serious drawback for many profiles is that in the 2M method, parts of the irradiance profile further away from the center of the profile are weighed heavily, so that often the 2M beam diameter is obviously too large for a physical, and especially for a “thermal” diameter.

2.3 The “Most Restrictive Ratio” method

In the latest edition of IEC 60825-1 (Edition 2.0) an image analysis method is specified in Paragraph 8.3 d) for general image profiles. This method was in previous editions of the standard specified to be used to analyze multiple sources, i.e. arrays, and is now generalized for all non-top hat profiles. The principle is to analyze a non-homogeneous source in respect to the most restrictive combination of power contained within a certain part of the source image and the angular subtense of that part of the source. The partial power is compared to the emission or exposure limit, and the angular subtense is used to calculate the exposure or emission limit. In the strict sense, all but a constant irradiance profile (a top-hat profile) could be considered as non-uniform source. The most restrictive combination of power within an area of the image and the diameter of that area is the one where the ratio of (power within area)/(diameter of area) is maximum. We refer to this method as the Most Restrictive Ratio, MRR, method (no “official” name is given to the method in IEC 60825-1 Ed2.0).

This technique lends itself very well to the evaluation of CCD images, where the signal of each pixel is characteristic of the local image irradiance. Parts of the image can be integrated up over an area (an evaluation ‘window’) which varies both in size and position on the image. The evaluation area, or ‘window’ is chosen as rectangular here, in order to simplify algorithms, but may also be circular (a rectangular evaluation area yields the more conservative results, as for the same characteristic diameter, the power that is contained in a rectangle is larger than the power contained in a circle of the same diameter). The width and the length of the rectangle is limited to small values by the value that corresponds to α_{min} = 1.5 mrad (which in terms of a CCD image is equivalent to a certain number of pixels) and to large values by α_{max} which is currently a constant value of 100 mrad. The parameter equivalent to α in the laser safety MPE values, for a non-circular case (or non-square case) is determined by the arithmetic mean (a+b)/2, as usual for ‘oblong’ sources and as described in IEC 60825-1. Each evaluated area contains a certain partial power P_i and has a certain ‘diameter’ δ_i associated with it, for instance as shown for i=1 with white lines in Figure 2.

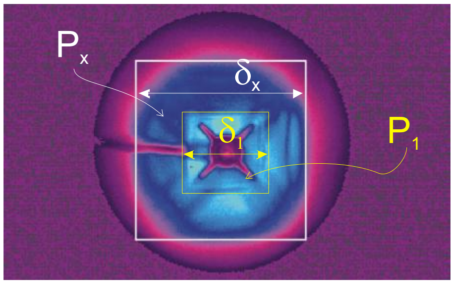


Figure 2. ‘Most restrictive ratio’ (MRR) analysis of an image that was produced by a LED in terms of most restrictive ratio of power contained within an area and characteristic diameter of that area δ.

The relevant “most restrictive” evaluation window is the one with the maximum ratio of P_i / δ_I, since the partial power, as for instance accessible emission level, will be compared to the limit (e.g. AEL) and the limit itself depends on the value of α. For the example of the image of the LED shown in figure 4, this most critical area is shown with a white frame, and the corresponding level of partial power P_x is then used in the comparison to the exposure limit or product emission limit, while the ‘diameter’ δ_x of the critical part of the image is transformed into an angular subtense and is used as value of α to determine the MPE or the emission limit. This principle is equivalent to analyzing multiple sources as described in the appendix of IEC 60825-1 (already in Edition 1) where the power that is contained in individual sources is related to the angular subtense of the partial source and different combinations of sources are analyzed (usually it is simple to show that the single source is always the most critical one except when the sources are very close together). The method is a generalization of the method given in IEC 60825-1 Edition 1 for discrete assemblies of sources to inhomogeneous images.

When this MRR method is applied to a Gaussian beam profile, then a diameter which encircles 72 % of the total power results, i.e. a diameter which in size is between the d_{63} and the d_{87} diameter. However, for a comparison of the diameter definitions it needs to be considered, that in contrast to the usual application of the d_{63} diameter for the determination of a, for the MRR method, it is not the total power that is compared to the exposure limit or emission limit, but only 72 % of the total power (or rather, of the power that is measured through the applicable aperture and with an open field of view).

2. MATERIALS AND METHODS

The computer model used in the present study is an extended "Thompson Gerstman" model and was described in [8]. The model was validated by comparison with a bovine explant ex-vivo model as well as by comparison with NHP threshold data. The wavelength for which the validation with the bovine explant was performed was 532 nm and the computer model threshold data presented here also uses the absorption parameters applicable for radiation with a wavelength of 532 nm. Temporal pulse profiles were rectangular.

In this work, the damage thresholds for two different types of profiles were calculated: rectangle, and ring. For both types of profiles, the size as well as the pulse duration was varied. For the rectangle, additionally to the "size", also the aspect ratio of width and height was varied, for the ring, the thickness of the ring was varied. The damage threshold of the respective profile for a given pulse duration, $Q_{\text{thresh profile}}$ is given in units of mJ and constitutes the total energy per pulse at the level of the retina, i.e. the total energy within the profile that just produces (for a given profile and pulse duration), a minimal visible lesion.

The MRR method was applied to each profile to determine the thermally effective diameter D_{therm} in units of µm and the corresponding partial energy Q_{part}. Important here is that the dimension of the evaluation area is limited by α_{max}. For the value of alpha max, we have used both the current constant value of 100 mrad as well as the pulse duration dependent value as proposed by Schulmeister et al. [7]. We use the thermally effective *diameter* D_{therm} here, rather than an angle, as this value is more directly related to for instance a CCD image. However, this parameter D_{th} is also directly related to an "angular subtense" α by division by the appropriate length of the eye (17 mm for a human). This angular subtense α can be used to determine the MPE or AEL in an actual safety evaluation. Ideally, the MRR method should result in a scaling of D_{therm} and the partial energy that reflects the actual damage threshold of the respective retinal profile. It is important to see the value of D_{therm} and the partial energy as a pair, since D_{therm} is used to determine a and this is the parameter that scales the MPE or the AEL, and the partial energy is compared to the MPE or AEL. It is also useful to introduce an energy fraction factor F so that the partial energy $Q_{\text{part}} = F \cdot Q$ where Q is the total energy within the profile. F would be a value between 0 and 1.

This concept of partial or fractional energy unfortunately complicates a comparison of the actual damage threshold with the MRR method that is used for an MPE or AEL analysis. The damage threshold $Q_{\text{thresh profile}}$ is specified as total energy within the profile, while the MRR method results in a characteristic profile parameter D_{therm} (the "thermal" diameter) and it is only the partial energy within the critical evaluation rectangle that is to be compared to the MPE or the AEL.

Since the top-hat distribution is the only distribution with a clearly defined diameter, it is taken as the basis for the comparison with other profiles. The principle of comparison is shown with an example: assume that for a top-hat profile with an outer diameter of 25 µm (α = 1.5 mrad, i.e. a minimum retinal spot size), the damage threshold equals 10 µJ for a given pulse duration and wavelength. The threshold for a larger top-hat shaped distribution will be larger, for example for an outer diameter which equals 250 µm (α = 15 mrad), the threshold could be 100 µJ (for the same pulse duration and wavelength). The ideal criterion for the determination of α for an arbitrary retinal profile is one which produces a value of D_{th} = 250 µm (α = 15 mrad) as "thermally characteristic diameter" for any profile which also has a threshold of 100 µJ.

We have used two criteria to evaluate the MRR method for arbitrary retinal irradiance profiles: the safety factor of the profile SF_{profile}, and a quality factor k which is derived from the ratio of the damage threshold of the profile that is evaluated, $Q_{\text{thresh profile}}$ and the predicted damage threshold of a top hat profile determined for the value of α that is the "output" of the MRR method. The safety factor is the ratio of the damage threshold of the profile $Q_{\text{thresh profile}}$ and the MPE(α), corrected with the fraction F of the power that is inside the most restrictive evaluation rectangle and that would in a safety analysis be used to reduce the power. Also, since the MPE is defined at the corneal level, the transmissivity of the ocular media in front of the RPE, T have to be taken into account.

$$SF_{profile} = \frac{Q_{thresh\ profile} \cdot F}{MPE(\alpha) \cdot T}$$

This safety factor can be used as a criterion if the result of the MRR method, together with the specified dependence of the MPE on α, produces an acceptable safety factor. Sliney et al. [9] argue that a safety factor of 3 would be acceptable if there is little uncertainty and variability, and Lund et al. [10] found that for instance for 100 ms pulse duration non-human primate threshold studies with a green wavelength laser the safety factor is 3. It is noted that a direct derivation of the safety factor from the computer model that is validated with explant ex-vivo threshold data and NHP data, that would apply to humans is difficult. There are factors of pre-retinal loss as well as of tissue temperature and pigmentation, which all affect the damage thresholds, in different ways for humans and non-human primates.

A quality factor k can be defined as the ratio of the damage threshold of the profile and the damage threshold of a top hat profile that has the "diameter" a which is the result of the MRR method, corrected with the fraction factor F:

$$k = \frac{Q_{thresh\,TopHat}(\alpha)}{Q_{thresh\ profile} \cdot F}$$

The factor k as a quality describing value (it is actually 1/ quality) and ideally would be 1, which expresses that the threshold of the profile has the same threshold as a top hat with diameter α (α is the result of the MRR analysis) corrected with the fractional factor F which is also a result of the MRR analysis. If k is larger than 1 it would produce an α which is too large and/or a factor F which is too small, producing a result that errs on the wrong side of safety. We will see for the example of a thin line for short pulses, that the value of k can be large for the case of a constant value of 100 mrad for α_{max}, which would indicate that the quality of the MRR method for these conditions are not acceptable. However, for short pulses and a constant α_{max} of 100 mrad, the MPE, for a top hat profile for extended sources have a large enough safety factor so that the overall result would still be acceptable, because the safety factor of the profile is still larger than 3. One could say that the quality of the MRR method for α_{max} = 100 mrad is "bad", but so is the MPE for extended sources and short pulses as long as α_{max} = 100 mrad., having an unnecessarily large safety factor.

The value of k can also be seen as factor that reduces the safety factor for a top hat of angular subtense α. If k is for instance 10, then this means that the safety factor for the profile under investigation is a factor of 10 smaller than the safety factor of a top hat profile with angular subtense of α. If this latter safety factor is for instance 30, then the safety factor of the profile would be 3 which is deemed acceptable. When the value of k can be seen as an inverse quality factor of the method, the safety factor of the profile is more like the criterion which decides if the method is actually acceptable or not. The above formula for k also results from the ratios of the safety factors since the MPE(α) and T cancels out:

$$SF_{profile} = \frac{Q_{thresh\ profile} \cdot F}{MPE(\alpha) \cdot T} \qquad SF_{TopHat} = \frac{Q_{thresh\ TopHat}(\alpha)}{MPE(\alpha) \cdot T} \qquad k = \frac{SF_{TopHat}}{SF_{profile}} = \frac{Q_{thresh\,TopHat}(\alpha)}{Q_{thresh\ profile} \cdot F}$$

If the MPE would follow the spot size dependence of the top hat profile threshold „perfectly" for all pulse durations and spot sizes, a value of k = 1 would mean that also the MRR method would be "perfect" - where perfect means a safety factor which is neither too small so that the MPE would be too close to actual damage thresholds nor an unnecessarily large safety factor which would needlessly restrict products and applications to too low emission or exposure values. For the case where the safety factor of the top hat profile is needlessly large, a large factor of k does really mean the MRR method under investigation is unacceptable. The final acceptability criteria is the safety factor of the profile not being less than a critical value, here we use 3 as the critical value.

3. RESULTS

3.1 Rectangular Profile

We have calculated the damage thresholds for rectangular profiles for varying size and aspect ratio. For a given width of the rectangle, for instance 30 µm, we varied both the height as well the pulse duration. Maximum size was 2.1 mm, and pulse durations between 10 µs and 1 s were used.

3.1.1 Rectangular Profile, time dependent α_{max}

For the case of a time dependent α_{max}, the largest value of k (indicating the lowest "quality" of the MRR method) is found for long exposure durations and long thin lines, as shown in figure 3.

The largest value of k is found to be 1.8 for 200 ms pulses and a height of the rectangle of larger than 1.5 mm. For smaller rectangles, the value of k decreases and for many pulse durations and rectangular sizes has the value of about

0.8, which is equal to π/4 and stems from the difference of a circular area for the top hat and a rectangular area and rectangular evaluation area for the rectangular profile.

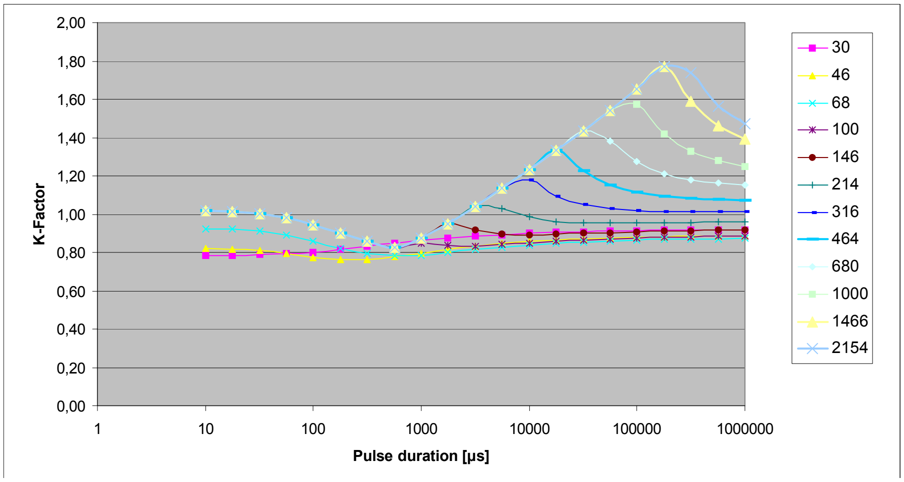


Figure 3. The inverse quality factor k for rectangles with width 30 µm for different heights, up to 2.1 mm and for pulse durations between 10 µs and 10 s, for the case of a time dependent α_{max}.

A factor 1.8 would indicated that the MRR method produces values of α and F which are somewhat on the side to decreased safety as compared to the top hat. However, this value on its own is not enough information to decide if the MRR method for this case produces good, or at least acceptable results or not. It is necessary to also consider the safety factor of the rectangular profile on its own, which is shown in figure 4.

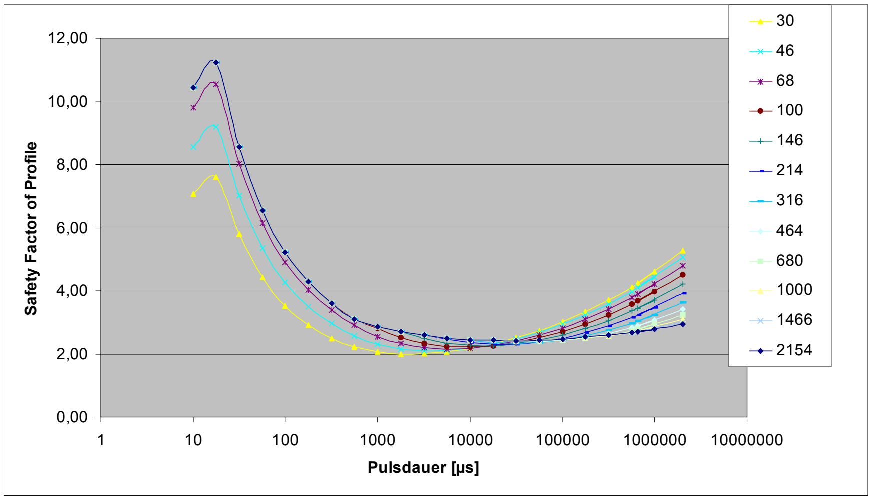


Figure 4. Safety factor for a rectangle with width 30 µm for different heights up to 2.1 mm and different pulse duration, not corrected for pre-retinal transmission losses and tissue temperature.

The plot of the safety factor Fig. 4 shows that it is actually not the long duration pulses - where k was largest – have the lowest safety factors, but pulse duration in the range between 1 ms to 100 ms, especially for short lines. Taken together with the correction for transmission losses and tissue temperature, the MRR method yields results that should be acceptable, even for those combinations of rectangle size and pulse duration which produces the lowest safety factor. It is noted that the lowest safety factor (2 if uncorrected) is associated to a 30 µm x 30 µm square, i.e. practically small source conditions. The computer model for these small spots yields damage thresholds that are about a factor of 3-4 lower than the NHP data as discussed in Schulmeister et al. [8]. Therefore, a safety factor for small spots of 3 based on computer model data corresponds to a safety factor of about 10 for NHP data.

3.1.2 Rectangular Profile, time dependent α_{max}

For the case of a constant value of α_{max} of 100 mrad, for the same set of rectangles as shown in figure 4 the value of k is found for short pulses, as shown in figure 5. The value of k can reach values of up to almost 12, indicating a “poor quality" of the MRR method. This poor quality is due to the lack of time dependence of α_{max}: the biophysical damage threshold has an α square dependence but the current MPEs feature an a dependence up to values of α = 100 mrad.

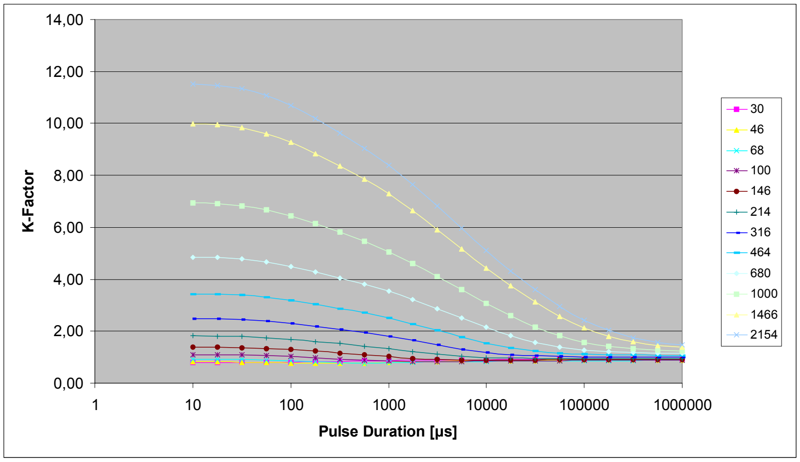


Figure 5 The inverse quality factor k for rectangles with width 30 µm for different heights, up to 2.1 mm and for pulse durations between 10 µs and 10 s. The largest value of k is found for 10 µs pulses and a height of the rectangle of 2.1 mm, to be almost 12.

It is therefore not the MRR method as such which is of poor quality, it is that the maximum area of evaluation is not limited to the time dependent values but is allowed to increase up to 100 mrad. This produces a value of α which is "too large" and for this large value of α, the safety factor for a top hat for short pulses is very large. As is shown in figure 6, the safety factor for the MRR method should be acceptable.

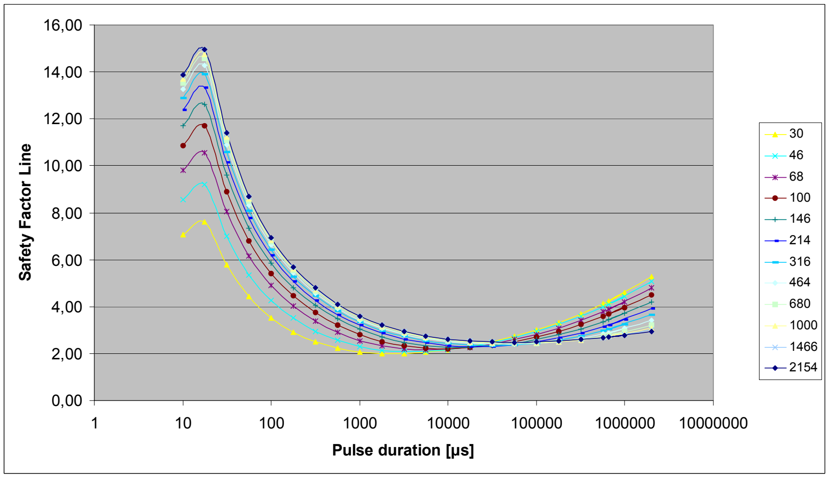
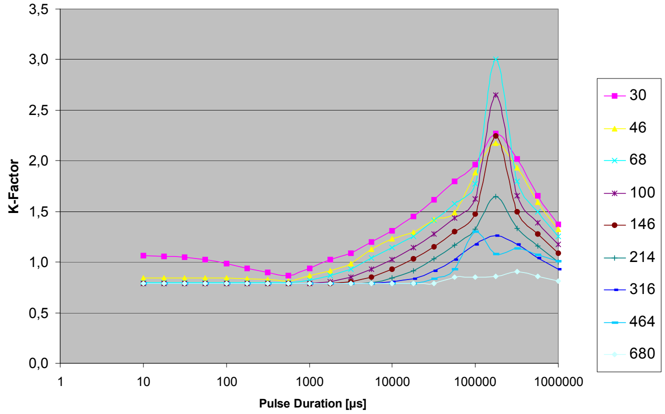


Figure 6 Safety factor for rectangles with width 30 µm, not corrected for differences of model.

3.2 Ring shaped profiles

For a given outer diameter, a ring shaped, or annular retinal irradiance profile generally has a lower damage threshold than a top hat with the same diameter for the same pulse duration, when the damage threshold is specified in terms of total intraocular energy or on the corneal plane. The lower damage threshold when stated as total power is due to the higher concentration of the power into a smaller irradiated area than compared to a top hat profile with the same outside diameter. It follows, that an appropriate method to determine α should for a ring yield a smaller value of α, at least when it is a method where the total energy in the profile is compared with the respective AEL or MPE. A ring shaped profile can be the result of imaging the near field of an unstable resonator, or be part of an emitter like an LED with a reflecting cup around the chip, or can be result of a directed diffuser. Damage threshold for a non-human primate model for nanosecond pulse durations where published in [11] where the damage threshold for top hat with outer diameter 300µm was 72 µJ while for a ring it was lower, 51 µJ. A ring shaped profile can be seen as a special test for a thermal beam profile analysis method, as it is an example where traditional beam diameter criteria doe not work. For instance, the 63 % of the total power method would yield a value of α which is smaller than for the top hat, which goes into the wrong way of safety. The result is even more extreme for the second moment method, where the 2nd Moment diameter of a ring is larger than the outer diameter of the ring. The method of 1/e for the case of a ring yields two possible values for α, namely the outer diameter and the inner diameter.

3.2.1 Ring - Time dependent α_{max}



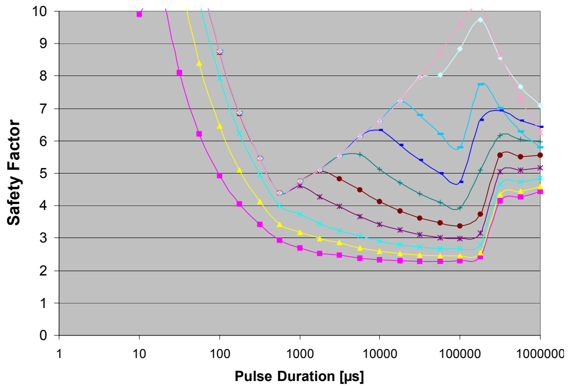


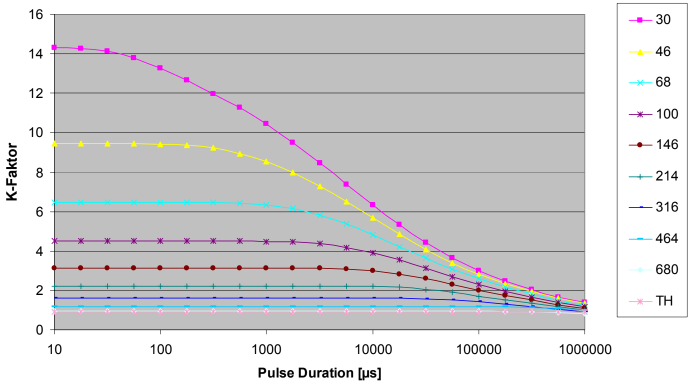
Figure 7 Inverse quality factor k for a ring shaped profile with outer diameter of 1.7 mm for a time dependent α_{max}. Right: **Figure 8.** Safety factor for figure 7, not corrected for differences in models.

The largest factor of k occurs for thin rings and around 100 ms exposure duration. The k factor for these conditions reaches values of up to 3, which decreases for shorter pulses and thicker rings. Again the k factor on its own is not enough to judge the acceptability of the MRR method. This is better done with the plot of the safety factor, figure 8. The erratic behavior of both the safety factor as well as the k-factor about around 100 ms comes from the change of the most restrictive evaluation area being based on the ring thickness for shorter pulses and being based on the full ring for longer pulses. At about 100 ms, this rather abruptly changes.

3.2.2 Ring – constant α_{max} = 100 mrad

For a ring with outer diameter of 1.7 mm the inverse quality factor k is plotted in figure 9 for a constant value of α_{max} of 100 mrad. For thin rings and short pulses the factor k reaches values of up to 14, which on its own would indicate a "bad" quality of the MRR method. However, as can be seen in figure 10, the safety factor of the ring when the MPE is determined with the value of a that results from the MRR analysis with constant α_{max} of 100 mrad has a large enough safety factor.

For thick rings and short pulses the safety factor reaches values of up to 320 nm, for the present constant value of constant α_{max} = 100 mrad (not shown in the figure).



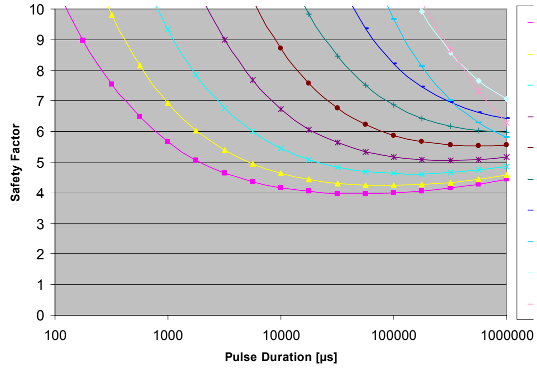


Figure 9 Inverse quality factor k for a ring shaped profile with outer diameter of 1.7 mm for a time dependent α_{max}. Right: **Figure 10.** Safety factor for figure 7, not corrected for transmission losses.

3.3 Scanning

With comparison to a stationary beam with a given pulse duration, beam profile and wavelength, a spot that scans across the retina is less hazardous (when the scan duration is for instance equal to the pulse duration of the non-scanning case). So far there is no bioeffects based guidance available how this decreased level of risk can be accounted for by increasing the allowed power of the laser beam entering the eye. In some cases, a safety analysis was based on the scan length, i.e. α was determined based on the scan length instead of the actual laser beam profile. Although the scanned beam, as perceived by the eye appears as a line, it is thermally only a line if it is fast enough so that it is within the thermal confinement time, which is usually not the case. It is, however, obvious that a scanning beam is more hazardous than if the energy that is delivered to the retina is distributed over an actual line on the retina, because a moving spot creates far higher temperatures than the equivalent line: after all, one does not use a line laser to weld metal, but a moving focused spot.

We have calculated damage thresholds for a number of scan speeds, retina spot sizes and number of repetitions of scans. Figures 11 shows the basic set up: a top hat or a Gaussian laser beam profile with a given diameter D scans over a line. Since the center of the spot at time $t = 0$ is on top of the point where we consider the starting point $x = 0$ of our scan, the locations left of $x = D/2$ are not exposed to the full exposure duration as are points to the right of $x = D/2$ since for these latter points, the full beam profile scans across.

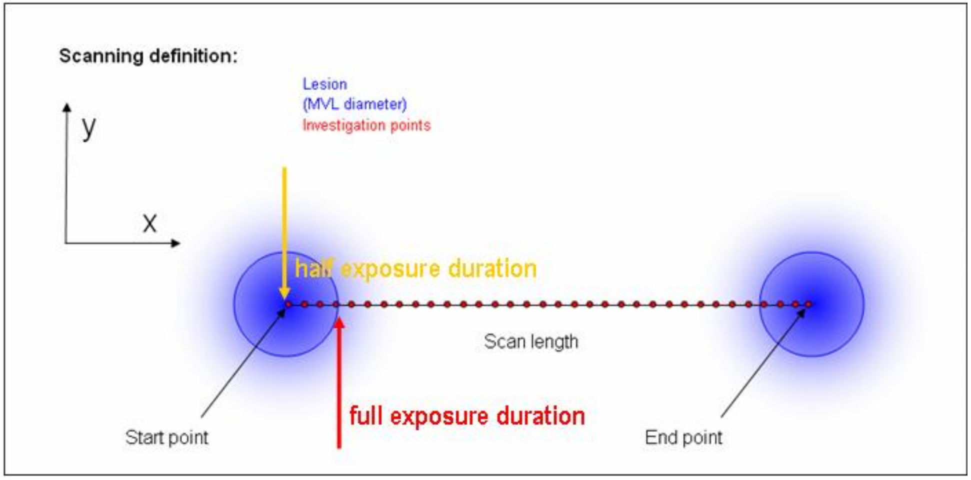


Figure 11. Principle scan set up explaining edge effects of single scans.

This decreased exposure duration for edge points explains why the local damage threshold is higher than for the points in the scan which are more than a distance of D away, as shown in figure 12 and indicated by vertical lines.

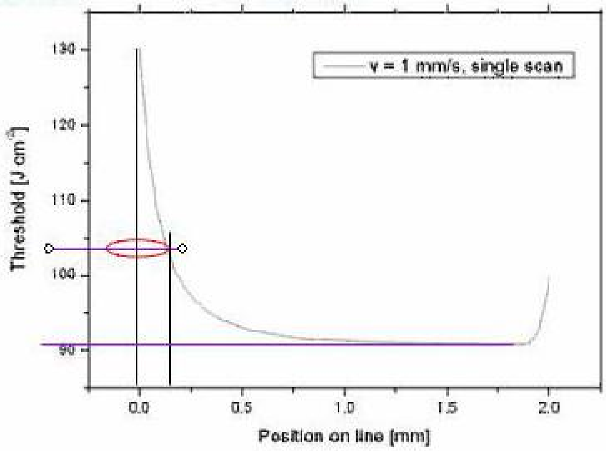


Figure 12. Local damage thresholds for a single scan with diameter of 288 µm top hat profile and a scanning speed of 1 mm/s and a scan length of 2 mm.

Beyond the second vertical line which marks the radius of the spot, the local damage threshold decreases further along the scan path due to the influence of the neighboring region on the scan line (the ones that were heated previously to the spot at the point x under consideration, i.e. to the left), where the temperature at spot x is higher due to this heated neighbors. The threshold at the end of the scan increases again due to a lower exposure duration of the end-region of the scan x = 2 mm (partial coverage by the beam), however, the heating effect of preheated neighbors results in a threshold at the final spot that is much lower than at the beginning of the scan (x = 0), where both have the same exposure duration. In the central part of the scan, however, the influence of the pre-heated neighboring area is not great, it is about 10 – 15 %. In spite of this influence of the neighboring area, we will see below that this central region can be treated quite well with an equivalent pulse duration approach, at least for the conditions investigated in this report.

For multiple scans, the situation at the endpoints is drastically different as can be seen in figure 13.

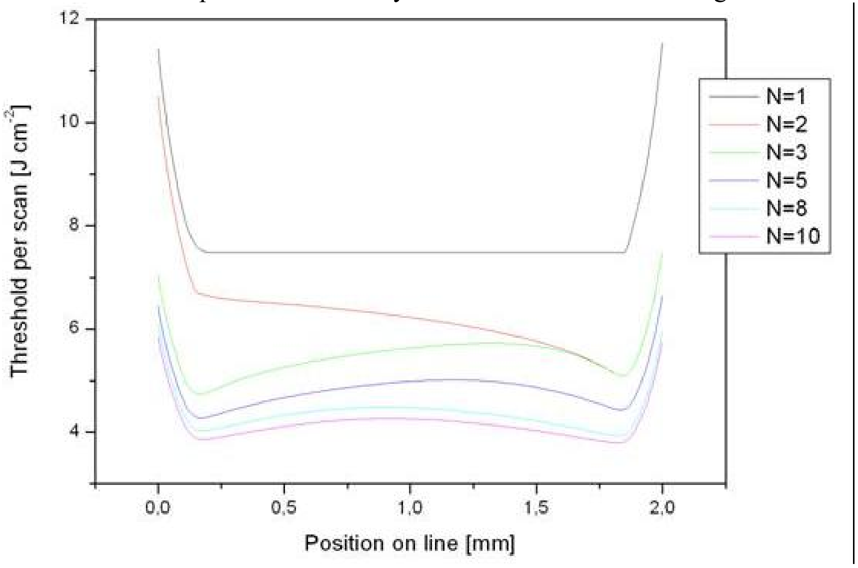


Figure 13. Local damage threshold for multiple scans, for a spot size of 288 µm top hat profile, and a scan speed of 100 mm/s (i.e. 100 times faster as in figure 12). N denotes the number of scans, where the scans where of alternating direction.

For a single scan, due to the relatively fast scan speed, there is practically no decrease of damage threshold along the line. However, for multiple scans, the end-regions exhibit drastically decreased damage thresholds not only compared to the case of a single scan but also compared to the central region of the scanned line. This is *not* due to a decrease of scan speed: we have assumed that the scan speed remains constant up to the turning point and then turns around within one time-step of modeling, which is thermally an instant turn around. The decrease of the threshold in the endpoints is rather due to the prolonged exposure since there is practically a doubling of the exposure duration as compared to the center of the line, with no cooling in between. The non-symmetric shape of the lines stem again from the influence of heighted neighbor regions which lead to a higher temperature as compared of the single heated spot.

For a single scan, where the end-regions have a higher damage threshold than the center piece (i.e. are less critical), comparison with model results for an equivalent pulse show that this is a valid method for a simplified safety analysis, at least for the wavelength of 532 nm and for top hat or Gaussian beam profiles. What is meant here that the scanning beam profile, in the following plots assumed to of Gaussian profile, moves across a given point in the center of the scanned path. For this point, a scanned exposure applies: for a spatial Gaussian profile, the temporal pulse profile is also Gaussian. When the pulse duration for this scanned exposure is determined with as FWHM, and a damage threshold in terms of peak irradiance during the pulse is determined for a Gaussian beam profile and Gaussian temporal profile pulse with pulse duration of FWHM, then this threshold is found to be well comparable with the local threshold of the scanned point, as can be seen in figure 14.

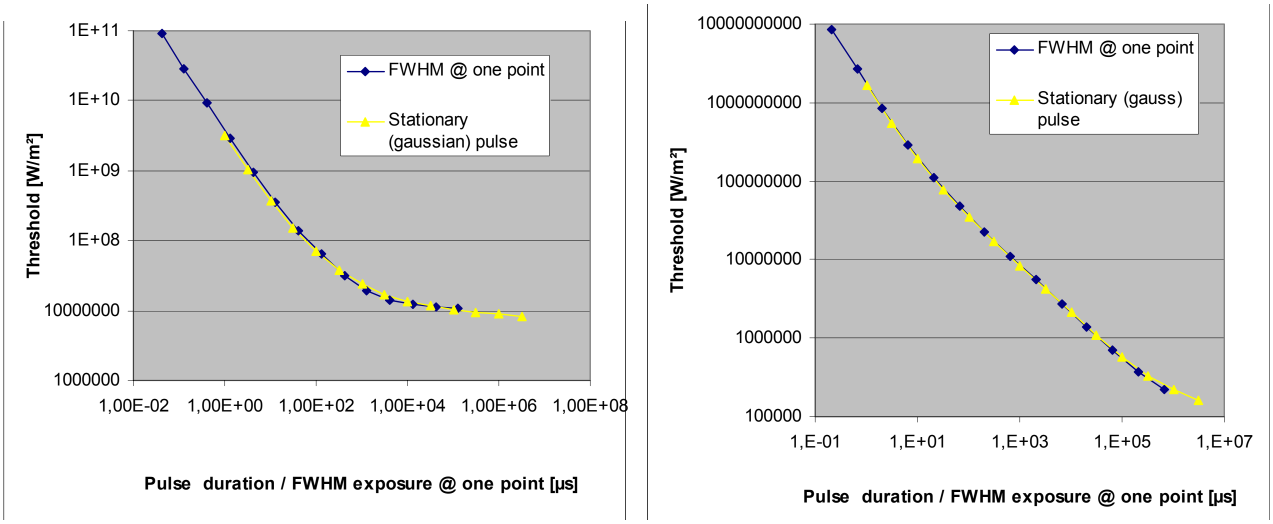


Figure 14. Comparison of the local damage threshold calculated for a scanned exposure of a spot in the center part of the scan path, with the calculated damage threshold for a temporal Gaussian pulse where both have the same FWHM pulse/exposure duration. Left for a 25 µm (1/e) Gaussian spot, right for a 1 mm Gaussian spot.

However, obviously this method <u>can not be applied</u> if there are multiple scans along a line since the damage threshold is then much lower (not only at the turnaround point, compare for instance N = 1 with N = 2 in figure 13). It can also not be applied if the retina is covered with a raster of lines, where the lines are close enough so that one lines thermally affects another scanned line. The thermal effect meant here is not only restricted to residual elevated temperatures due to a previous scan being still present when the scan path under consideration is scanned, but also when the scans are temporally far enough apart so that the position under consideration has cooled down before it is actually scanned. In the latter case, the damage threshold is still lower than for the non-pre-affected case since the cells can be considered partially damaged by earlier thermal insults – this is equivalent to multiple pulses where the $N^{-1/4}$ rule also applies to pulses that are temporally far enough apart so that complete cooling occurred during the pulse. Both can be explained well with the integration of the temperature over time with the Arrhenius integral (see [12] for a discussion on multiple pulses).

It is also instructive to plot damage thresholds as function of scan speed for four different Gaussian retinal irradiance profiles (1/e diameter), figure 15. It can be seen that for high scan speeds, the dependence of the damage threshold is linear with scan speed, which expresses that the fast scan has the same effect as a non-scanned line, i.e. the scan is fast enough so that thermally the scan path appears to be heated instantaneously and all points at the same time. For smaller spots, this critical time appears to occur at lower scan speeds than for large spots. On the slow scan speed end, the damage threshold approaches an almost horizontal line, which however can not be expected to become an actual horizontal line, since the non-scanned damage threshold also is still dependent on exposure duration when expressed as irradiance level, even though if it is a very weak dependence (approximately $t^{-0.1}$).

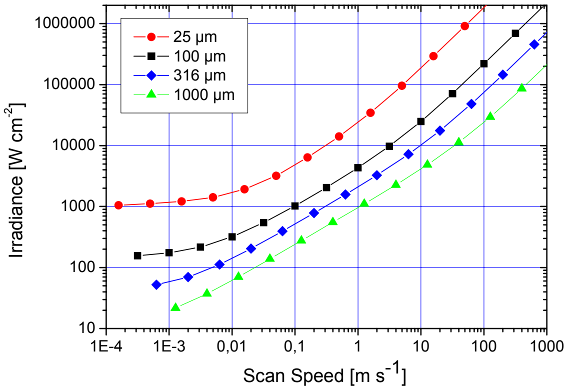


Figure 15. Calculated damage thresholds as function of scan speed for four different spot sizes for a Gaussian beam profile (1/e).

How much less hazardous (which could for instance be expressed by a correction factor such as C_6 for extended sources) a scanned beam vs. non-scanning is, can not be derived from the plots such as Figure 15 if a non-scanned spot with a given pulse duration is compared with a scanned exposure where the total scan duration equals the pulse duration: the hazard of a scan depends strongly on scan speed (and spot diameter), but also on edge effects, and it is the scan speed and scan length together with the number of scans that is related to the total scan duration.

4 CONCLUSIONS AND SUMMARY

For top-hat rectangular pulses with varying aspect ratio, size and pulse duration, and for annular retinal exposure patterns, for 532 nm radiation, the most restrictive ratio method as required in the 2nd edition of IEC 60825-1 appears to be a valid method, although calculated safety factors are for special cases in the lower range of acceptable safety factors. Although the method results in acceptable results also for the case of α_{max} = 100 mrad for all pulse durations, the method yields biophysically reasonable results only if the proposed time dependent α_{max} is adopted.

For scanned exposures, for single scans of top hat or Gaussian beam profiles in the visible, an equivalent single pulse can be used to derive the applicable MPE for the same FWHM that a spot on the scan would be exposed to. This simple method does not apply to multiple scans and to raster exposure of the retina.

For more complicated retinal irradiance patterns or scanned exposure of the retina, the computer damage model can be used for a safety analysis.

ACKNOWLEDGEMENTS

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