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DAMAGE THRESHOLDS FOR IRREGULARLY PULSED EXPOSURE OF THE RETINA

Paper 303

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Abstract

The international laser safety standard IEC 60825-1 in its second edition does not provide a method on how to analyse pulse trains with irregular pulse peak powers. A retinal thermal injury model is used to study examples of pulse trains with irregular peak powers. It is shown that if an individual pulse is only a factor of 1.5 higher in power than the other pulses of the train, for the conditions studied (small source, 532 nm wavelength, cooling between pulses) the retinal damage is induced solely by the one higher pulse and the other pulses do not contribute to the damage process. For this case, the $N^{-1/4}$ rule is overrestrictive and the Total-On-Time-Pulse rule can seriously understimate the risk and shall not be applied to analyse pulse trains with varying pulse peak power. As any standardised method to analyse irregular pulse patterns that will be developed in the future will be rather a worst case approach, the retinal thermal damage model developed by the Austrian Research Centers Seibersdorf can be used as a validated tool for hazard analysis of specific emission patterns for pulse durations in the millisecond regime.

Introduction

The international laser safety standard IEC 60825-1 [1] specifies how the exposure evaluation or classification of a laser product is to be performed for the case of multiple exposure or emissions, respectively. The corresponding paragraph for the classification is 8.3.f. With the acceptance of the classification based on IEC 60825-1 by the CDRH (CDRH Laser Notice 50), the following is also relevant for marketing lasers in the USA.

We restrict our discussion to the evaluation of retinal thermal limits for pulse durations above 18 µs.

IEC 60825-1 specifies three evaluation criteria for multiple pulses: 1) the single pulse criterion, 2) the average power criterion and 3) a criterion which could be referred to as "additivity criterion". For criterion 3), in the current edition 2.0 with corrigendum, 3a) is specified "for constant pulse energy and pulse duration", and 3b) is to be used "for varying pulse widths or varying pulse intervals". 3a) is commonly referred to as the "$N^{-1/4}$ rule", and 3b) as the "Total on time pulse rule" (TOTP Rule). These methods are in more detailed discussed in Henderson & Schulmeister [2]. It is interesting to note that the case of *varying peak powers* is *not covered* by IEC 60825-1 edition 2.0. We will see in this paper, that for the case of varying peak powers, the $N^{-1/4}$ rule would in many cases be over-restrictive, while the TOTP rule would err significantly on the wrong side of safety, i.e. be not restrictive enough, and should NOT be used for the case of irregular peak powers.

Retinal Thermal Injury Model

A thermal retinal injury model was developed at the Austrian Research Centers Seibersdorf that was validated by comparison with damage thresholds from both ex-vivo exposures as well as non-human primate exposures [3]. The model is available as tool for the safety evaluation of products where the methods given in IEC 60825-1 would have to be based on worst-case assumptions, as for the case of scanned retinal exposure (see Paper 301 of these proceedings), or for the case of irregular multiple exposures (this paper) where currently no evaluation method is specified for the case of varying peak power.

Regular Pulse Trains

The results of the injury model as summarized here are in more detail discussed in reference [4] and apply to the wavelength of 532 nm and for top-hat retinal exposure profiles.

The multiple pulse threshold data presented in reference [4] follow the TOTP rule trend well for two cases:

a) when the spacing between pulses is small - being related to cooling between pulses
b) for longer pulse durations and small spots (the smaller the spot, the shorter the pulse duration for which the TOTP rule trend applies).

The dependence of the trend of the multiple pulse thresholds can be explained with the temporal variation of the tissue temperature (the so called 'time-temperature history') and the Arrhenius integral, further on referred to as damage integral

$$\Omega = C_1 \int_0^{t_{total}} e^{-\frac{C_2}{T(t)}} dt \qquad \text{Equ. 1}$$

where C_1 is a frequency parameter with units of 1/s, C_2 is proportional to the enthalpy and $T(t)$ is the temperature as function of time. The value of Ω represents the degree of thermally induced damage, the parameters C_1 and C_2 are chosen such that Ω reaches a value of 1 for a detectable lesion. Two features of the Arrhenius integral are important for the discussion of multiple pulse exposures: first, the value of the integral is highly non-linear with temperature, since the temperature is in the exponent, second, for a constant temperature level (i.e. when a steady state temperature is reached during the pulse), the integral can be split up into a sum of individual integrals.

The comparison of the experimental threshold data presented in Reference [4], with our thermal damage computer model (that is based on an Arrhenius damage integral) confirms the previous understanding of multiple pulse exposures in the thermal damage domain where each pulse introduces sub-threshold insult on the cell which adds up during the pulse train until a macroscopically visible lesion is observed. The Arrhenius damage integral allows a quantitative evaluation of the 'partial' damage that each pulse contributes to the minimal visible lesion.

The trend of multiple pulse thresholds as a function of pulse duration, retinal spot size, pulse spacing and number of pulses (but within the pulse train constant pulse duration and peak power) was evaluated against the trend that is predicted following the Total-on-Time Pulse (TOTP) rule as specified in IEC 60825-1. It is observed that the actual damage thresholds either follow the TOTP rule trend very well or lie above the TOTP-rule trend, i.e. in the second case the TOTP-rule trend errs on the safe side. The TOTP rule trend is followed well for two conditions: when the spacing between pulses is short so that there is little cooling between pulses and when the steady state temperature is reached during the pulse. If the pulse is shorter than the time needed to reach the steady state temperature, one 'total pulse' produces higher temperatures for the same radiant exposure than several split-up pulses which have the same TOT and total radiant exposure. Therefore, the threshold for thermal damage is higher when the pulses are split up as compared to one 'total pulse'. It is concluded that the TOTP rule is an appropriate method for safety evaluation of the thermal damage of multiple pulses *with constant peak power* even if a time dependent breakpoint α_{max} is introduced, as was suggested by Schulmeister et al. in [5]. In that case, since a time dependent α_{max} would in effect produce a time dependence of the exposure limit that depends on the diameter of the retinal spot size (i.e. of α), the $N^{-1/4}$ rule would no longer be an appropriate method since it is based on the time dependence of the exposure limit of $t^{3/4}$ and only for this time dependence is it identical to the TOTP rule.

Irregular Pulses - Introduction

It is important to note that the TOTP rules errs on wrong side of safety when applied to pulse trains with varying pulse peak power. This case, as discussed on the basis of damage thresholds for the first time in this paper, was not studied at the time when previous publications that cover multiple pulses, such as references 1, 2 and 4 were published. Due to this, in both Henderson and Schulmeister [2] it was implied that the TOTP rule is also the appropriate method for the case of varying peak powers. It is noted that IEC 60825-1 Edition 2.0 does *not* refer to the case of varying pulse peak powers – which is advantageous because requiring using the TOTP rule would be wrong, but on the other hand it is not ideal that a standard gives no advice at all for this relatively common laser radiation emission pattern.

The main reason why varying pulse peak powers are a challenging issue is the extreme non-linearity of thermally induced retinal damage. The strong non-linearity is expressed by the Arrhenius integral (Equation 1) where the temperature is in the exponent: a slightly higher temperature will lead to an unproportionally large Arrhenius integral or "damage" value.

Irregular Pulses – Injury Model

The following scenario was analysed with the thermal injury computer model: Wavelength: 532 nm; retinal spot size: 25 µm; irradiance profile on retina: top hat; spacing between pulses (pause): 10 ms; and two different pulse durations: 18 µs and 10 ms. For a pulse spacing of 10 ms and small spot sizes, the retinal temperature returns to body temperature before the beginning of the next pulse, thus the following discussion might not be applicable in the same way for larger spots and/or shorter pauses between the pulses when there might be a remaining temperature elevation at the time when the next pulse commenses. A pulse train of 17 pulses was modelled, consisting of a first pulse with varying peak power relative to the following 16 pulses which all had equal peak power.

Table 1 summarizes the results for the case of a pulse duration of 18 µs.

Table 1. Results of retinal thermal injury model for the case of 17 pulses with pulse durations of 18 µs and varying relative peak power of the first pulse.

Relative Power of 1st pulse	Thresh old [µJ]	Factor thr with higher pulse more haz than all equal	Relative increase of Tot Energy	train with higher pulse more hazardous
1	31	1,0	1,0	1,0
1,5	23	1,3	1,0	1,3
2	18	1,7	1,1	1,6
3	13	2,4	1,1	2,2
4	10	3,1	1,2	2,6
5	8	3,7	1,2	3,0

The peak power of the first pulse was varied from a factor of 1 (equal peak power) up to a factor 5 larger power than compared to the following 16 smaller pulses. The quantities in Table 1 were selected so that a comparision with the TOTP rule was facilitated. The second column in Table 1 is the calculated total energy threshold for the corresponding pulse train. That is, the total energy of the train under consideration was varied in order to determine the exposure for which the model would predict the onset of retinal injury – while keeping the relative power between the first pulse and the trailing pulses constant. For instance, for the case of 17 equal pulses, the total energy threshold was 31 µJ, or 31 µJ/17 = 1.8 µJ energy contributed to the total energy of the pulse train at threshold for each pulse. When the first pulse is twice as high as the trailing pulses (third line in Table 1), the calculated total energy threshold equals 18 µJ, of which 2.0 µJ is associated to the first pulse and 1.0 µJ is associated to each of the trailing pulses. However, we will see below that the damage in this case is solely due to the first larger pulse and the smaller pulses are irrelevant for the induction of damage, as 2.0 µJ is also the damage threshold calculated for a single pulse. The damage threshold specified as total energy (or radiant exposure) for the pulse train decreases with increasing power of the first pulse, which is not reflected by the TOTP rule, where the exposure limit (or emission limit for classification) remains constant since it is based solely on the TOT. The third column in Table 1 is the ratio of the threshold for the case of all equal pulses (i.e. 31 µJ) to the threshold of the pulse train under consideration. The fourth column is the relative increase of total energy due to increasing the first pulse relative to the trailing pulses compared to the case of 17 equal pulses. The values in the fifth column are obtained by dividing the third column with the values in the fourth column and could be a measure how much the TOTP rule would under-predict the actual trend of the damage threshold.

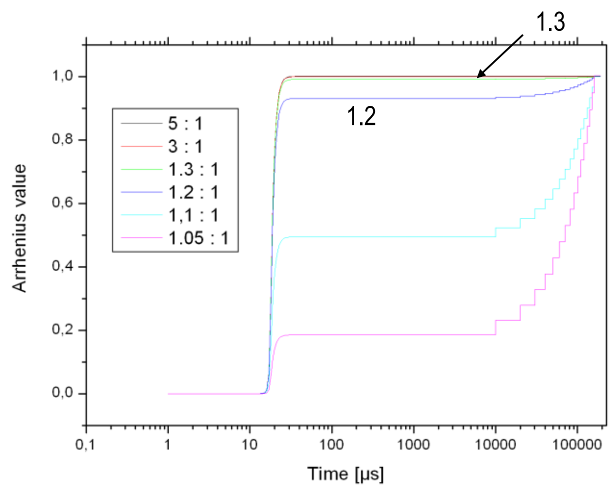

Figure 1. Plot of the Arrhenius integral value as function of exposure time for different ratios of the first pulse's peak power relative to the 16 trailing pulses. All pulse durations were 18 µs, pulse spacing was 10 ms.

It is instructive for the understanding to plot the Arrhenius integral value as function of time, as shown in figure 1. For the lowest curve, the peak power of the first pulse was only 5 % larger than the 16 trailing pulses, and it can be seen that the first pulse contributes almost 20 % to the damage intregral, while the 16 trailing pulses (of almost the same peak power) contribute only about 5 % each. The ratios are getting more extreme as the peak power of the first pulse increases relative to the trailing pulse. When the first pulse is 20 % higher than the trailing pulses, it already contributes more than 90 % to the damage integral (i.e., causes 90 % of the damage) while the 16 trailing pulses add only 0.6 % each to the actual "injury" that occurs at the end of the last of the 17 pulses. From a peak power factor of about 1.3 onwards, the retinal damage is induced solely by the first larger pulse and the trailing pulses contribute negligible amounts of partial damage. In that sense, it is irrelevant for the biophysical process how many trailing pulses follow the first larger one, and also where in the pulse train the larger pulse is located (at the end, the middle or der beginning). This also illustrates in another way why the TOTP rule is not appropriate: the damage is not induced by the pulse train as a whole, but solely by the one largest pulse (even if it is only a factor of 1.3 higher in power than the 16 trailing ones).

The results are similar for the case of pulse durations of 10 ms, as shown in figure 2. For a pulse duration of 10 ms and a small retinal spot, in contrast to the previous example of a 18 µs pulse duration, a steady state temperature is reached. The power factor for which the first pulse dominates the biophysical damage mechanism is somwhat higher than for the previous example and is approximately 1.5.

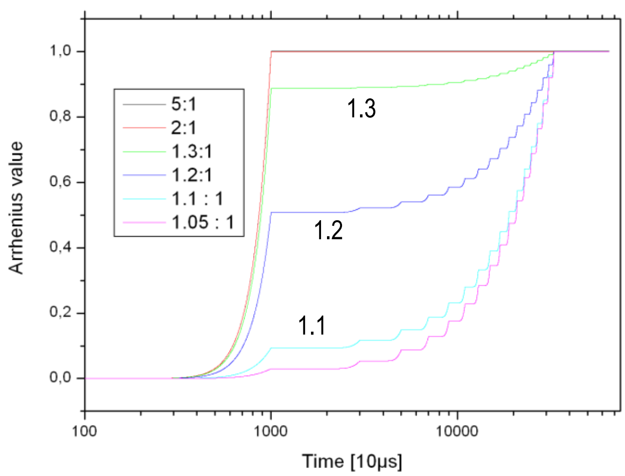

Figure 2. As for figure 1, but with a pulse duration of 10 ms.

Conclusions and Summary

For a minimal retinal spot size, 532 nm wavelength and a pulse spacing of 100 ms it can be concluded that from a pulse peak power ratio of about 1.5 upwards, retinal thermal damage is dominated by the single higher power pulse and smaller pulses would not have to be considered for safety evaluation or classification. Without further modelling it can not be predicted, however, what the critical power ratio for other spot sizes, other pulse spacings or wavelengths would be.

It should be noted that the present discussion strictly relates to thermally induced injury only, i.e. to pulse durations in the millisecond regime rather than for shorter (µs or ns) pulses, where the mechanism of injury at threshold is not thermal but micro-cavitation (bubble) induced (see references in [5]). For this type of damages, the additivity is expected to be of a purely statistical nature, as discussed by Lund et al. in Paper 302 of these proceedings.

It is important to note that the TOTP rule in the cases presented here seriously under-predicts the potential risk, i.e. would result in allowed output powers or exposure levels which are too high. On the other hand, the $N^{-1/4}$ rule is for these cases over-restrictive, as it would reduce the single pulse exposure limit based on the total number of pulses in the pulse trains while it would be sufficient to make sure that the largest pulse on its own is below the single pulse exposure limit. A possible (also worst case to some extent) approach which is not fully validated or developed at this point in time would be to adopt the evaluation method as specified for multiple wavelengths, where for each wavelength, the ratio of the exposure level over the corresponding limit is calculated and the sum of all ratios needs to be less than unity. The ratios could be formed with a TOTP rule approach for each “category” of peak powers. Whatever method is developed should consider that when α_{max} depends on the pulse duration, the $N^{-1/4}$ approachis only applicable for small source exposures; for extended sources different dependencies will apply. This dependence of the additivity on source size is represented in a straightforwad way by the TOTP rule.

As any standardised method to analyse irregular pulse patterns that will be developed in the future will be rather a worst case approach, the retinal thermal damage model developed by the Austrian Research Centers Seibersdorf can be used as a validated tool for hazard analysis of specific emission patterns for pulse durations in the millisecond regime.

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