ILSC® 2017 Conference Proceedings

Computer modelling to support laser safety analysis of irregular pulse trains

Mathieu Jean, Karl Schulmeister, Nico Heussner, Annette Frederiksen

Reference information for this proceedings paper

Title: *Computer modelling to support laser safety analysis of irregular pulse trains*

Author: *Jean M, Schulmeister K, Heussner N, Frederiksen A*

Proceeding of the International Laser Safety Conference, March 20-23, 2017 Atlanta, GA USA
Page 166-172

Published by the Laser Institute of America, 2017, Orlando, Florida, USA

COMPUTER MODELLING TO SUPPORT LASER SAFETY ANALYSIS OF IRREGULAR PULSE TRAINS

Paper #304

Mathieu Jean[1], Karl Schulmeister[1], Nico Heussner[2], Annette Frederiksen[3]

[1]Seibersdorf Laboratories, 2444 Seibersdorf, Austria
[2]Robert Bosch GmbH – Chassis Systems Control, 70465 Stuttgart, Germany
[3]Robert Bosch GmbH – Corporate Research, 71272 Renningen, Germany

Abstract

Neither the international laser safety standard IEC 60825-1 Edition 3.0 nor ANSI Z136.1-2014 provide specific rules of how to apply the pulse reduction factor C_5 (C_P) to irregular pulse trains. Without specific guidance, the analysis has to be performed based on worst case approaches, such as counting all pulses and giving them the same weight, even the ones with smaller peak power. The present study provides guidance on how to analyze irregular pulse patterns in a less restrictive way.

Introduction

In 2014, the third edition of IEC 60825-1 was published [1] as well as a new edition of ANSI Z136.1 [2]. For pulse durations longer than 5 µs in the wavelength range of 400 nm to 1050 nm and pulse duration longer than 13 µs in the range of 1050 nm 1400 nm, the rules of how to apply maximum permissible emission limits (MPEs) and accessible emission limits (AELs) to multiple pulses in both documents are equivalent. The rules for the analysis of multiple pulses for pulse durations less than the above differ, since in IEC 60825-1, a factor C_5 less than 1 applies for time bases longer than 0.25 seconds, while in ANSI Z136.1-2014 there is no reduction of the single pulse AEL that applies to pulse durations shorter than given above. In the following we will refer to IEC 60825-1 Edition 3.0 only, but the discussion also applies to ANSI Z136.1-2014.

The changes of IEC 60825-1 Edition 3.0 with respect to earlier editions were reviewed in an ILSC 2013 paper [3] as well as in a White Paper [4]. Specific issues related to the analysis of multiple pulses that are planned to be published in an Interpretation Sheet for IEC 60825-1 Edition 3.0 were discussed in an ILSC 2015 paper [5] and are repeated here.

The present paper relates to the rules laid down in subclause 4.3 f) of IEC 60825-1 which describe how classification of products with pulsed emission (or scanned emission that leads to a pulsed accessible emission pattern) has to be performed. As in previous editions, three criteria are given which have to be considered in parallel, i.e. it depends on the specific emission pattern which of the three criteria is the most restrictive one that limits the emission of a certain product to remain within a certain safety class (such as Class 1). The present discussion relates to the reduction factor C_5 and therefore to limits that can be associated with retinal thermal hazards (wavelength range of 400 nm to 1400 nm). The three criteria that apply in parallel (i.e. all have to be assessed and be complied with) can be described as follows:

1) *Single pulse criterion*

The accessible emission (AE) of each single pulse has to be below the single pulse AEL (i.e. the AEL determined for the pulse duration of the single pulse).

2) *Average power criterion*

The accessible emission expressed as average power (averaged over a certain time period) has to be below the AEL applicable for that averaging duration. For regular emission patterns (constant pulse duration, period and energy per pulse) the critical averaging duration is always equal to T_2 for Class 1 and equal to 0.25 s for Class 2. For irregular emission patterns, the averaging time period has to be varied, i.e. the AE and the AEL are both determined for some averaging time window that is varied both in terms of duration as well as in terms of temporal position within the pulse train. It was shown in reference [5] that the average power rule is equivalent to comparing integrated energy to the AEL expressed as energy; also Criterion 2) can be seen as extension of Criterion 1) when the shortest "averaging duration" used is the duration of a single pulse.

3) *Reduced single pulse criterion*

Criterion 3) calls for the application of C_5 (see rules for determination of C_5 below) to reduce the single pulse AEL, i.e. a more restrictive version of Criterion 1) (or the same for the case where $C_5 = 1$). As a basic rule, C_5 is a function of N and N is the number of pulses within T_2 (or 0.25 seconds for Class 2). This factor C_5 is applied to reduce the single pulse AEL, and the AE of every single pulse has to be below the reduced corresponding AEL. For a regular pulse train this is straightforward, but for irregular pulse trains there is the added complexity that groups of pulses have to be treated as "effective pulses", and N would then be the number of occurrences of the group within T_2. The AEL and AE is then determined for the group, i.e. the AEL is determined for the group duration and AE is the energy per group. This rule can be seen as extension of the average power rule when for each averaging duration, the region within the averaging duration is considered as "effective pulse", but additionally to just comparing the energy within the group to the AEL applicable for the group duration, that AEL is reduced by the factor C_5 derived from the number of groups within T_2.

While in the current standard wording, for Criterion 3) it is not specifically noted to apply C_5 for the case of pulse *groups*, based on basic biophysical reasoning (particularly if there is negligible cooling between the pulses within the pulse group) it is necessary to apply Criterion 3) not only to individual pulses but also to pulse groups (in ANSI Z136.1-2014 the grouping is specifically included in the wording). The necessity of the application of C_5 to groups of pulses is also expressed in the draft Interpretation Sheet I-SH 1 for IEC 60825-1 Ed. 3.0 [6].

In contrast to earlier editions of IEC 60825-1 as well as ANSI Z136.1, this grouping became necessary for the 2014 editions of the two standards, because in the latest edition, for emission durations longer than T_i, the reduction factor C_5 (C_P in ANSI) is limited to 0.2 (equivalent to only counting a maximum of 625 pulses) for apparent sources larger than α_{max} and to 0.4 (equivalent to only counting a maximum of 40 pulses) for apparent sources between 5 mrad and α_{max}. This limitation of the "extent" of the reduction of the AEL by the factor C_5 did not exist in earlier standards and as a consequence, considering individual pulses only (no grouping) and counting the number of individual pulses (compared to the number of pulse groups, the number of the individual pulses is always larger) the resulting C_5 applied to the AEL of individual pulses was always more restrictive as compared to considering a number of neighboring pulses as one effective pulse.

The following is a replication of the rules regarding C_5 currently specified in IEC 60825-1 Edition 3.0.

3) The energy per pulse shall not exceed the AEL for a single pulse multiplied by the correction factor C_5.

$$AEL_{s.p.train} = AEL_{single} \times C_5$$

where

$AEL_{s.p.train}$	is the AEL for a single pulse in the pulse train;
AEL_{single}	is the AEL for a single pulse (Tables 3 to 8);
N	is the effective number of pulses in the pulse train within the assessed emission duration (when pulses occur within T_i (see Table 2), N is less than the actual number of pulses, see below). The maximum emission duration that needs to be considered is T_2 (see Table 9) or the applicable time base, whichever is shorter.
C_5	is only applicable to individual pulse durations equal to or shorter than 0,25 s.

If pulse duration $t \le T_i$, then:

For a time base less than or equal to 0,25 s, C_5 = 1,0

For a time base larger than 0,25 s

If $N \le 600$ C_5 = 1,0

If $N > 600$ $C_5 = 5\ N^{-0,25}$ with a minimum value of C_5 = 0,4.

If pulse duration $t > T_i$, then:

For $\alpha \le 5$ mrad:

C_5 = 1,0

For 5 mrad $< \alpha \le \alpha_{max}$:

$C_5 = N^{-0,25}$ for $N \le 40$

C_5 = 0,4 for $N > 40$

For $\alpha > \alpha_{max}$:

$C_5 = N^{-0,25}$ for $N \le 625$

C_5 = 0,2 for $N > 625$

Unless $\alpha > 100$ mrad, where C_5 = 1,0 in all cases.

If multiple pulses appear within the period of T_i (see Table 2), they are counted as a single pulse to determine N and the energies of the individual pulses are added to be compared to the AEL of T_i.

Proposal for a "partial N"

For an emission pattern where pulses with high peak power per pulse are mixed with pulses with smaller peak power, to count all pulses as "1" for the determination of N is expectedly over-restrictive. That is, the AE of each pulse needs to remain below AEL · C_5, so that the pulse with the highest ratio of AE/(AEL · C_5) is critical in terms of compliance with a given class. When all pulses have the same peak power and pulse durations, there is no interpretation needed of the standard of how to count N (figure 1a). However, when the peak power of the pulses vary, to count all pulses with N=1 and to apply the resulting small C_5 to limit the peak power of the high pulse is intuitively over-restrictive.

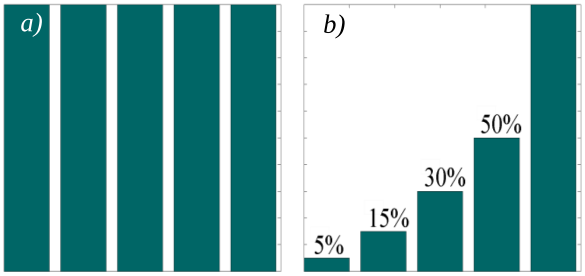

Figure 1. Straightforward comparison of two pulse patterns for which the AEL is identical (with N=5) although the pattern on the right (b) is obviously less hazardous for a given maximum peak power

In this paper, we discuss emission patterns with constant pulse duration but varying peak power (the pulses are assumed to be rectangular in temporal shape, i.e. the peak power during the pulse is constant), as well as varying period. This limitation to constant pulse durations was chosen in order to focus on the parameter N without tackling simultaneously the more complex problem of pulses of varying duration. In future work the analysis and proposals for varying pulse durations will be presented. In the present paper, we limit the discussion to thermally induced injury for pulse durations longer than T_i. For shorter pulse durations, the underlying damage mechanism in the cell is micro-cavitation (bubble formation) and cannot be approached with a model based on the Arrhenius integral.

For constant pulse durations, the draft Interpretation Sheet [6] for IEC 60825-1 states that "smaller" pulses (i.e. with lower peak power as compared to the pulse with the highest peak power) are not counted as "1" to increase N but as a "partial N", i.e. for the case of a pulse with peak power a factor of 5 smaller as the peak power of the "highest" pulse (the pulse with the maximum peak power), this pulse is counted as 0.2 to increase N; a pulse half as high as the highest pulse increases N by 0.5, and so on. Therefore, if within T_2 (assuming classification as Class 1 here) there is one pulse of maximum peak power (which increases N by 1) and 100 pulses with half the peak power, the resulting N equals 51. This method to determine N therefore weighs each pulse with the power relative to the peak power of the highest pulse which is also the pulse with the largest energy per pulse (AE) and therefore the critical pulse associated to the largest ratio of AE/AEL. It is noteworthy that the value of N determined this way is equal to the integral under the power "curve" when the maximum peak power is normalized to 1. Since the pulse duration is defined to be constant, the AEL is the same for all pulses. With this method of "partial N" there is still a certain additivity reflected by applying a reduction to the AEL that limits the AE of the large pulse, but it is not as strong as an analysis that counts small pulses as 1 for the determination of N.

The above-mentioned method should also be applicable to pulse groups. Whenever the emission consists of a repetition of identical pulse patterns (where only the peak power varies between consecutive patterns), these groups should be treated as an "effective pulse" and analyzed consequently. In other words, the "single pulse" AEL is given by the duration of the pulse group. The group of highest energy is assigned N=1m while the other groups account for a fraction of N depending on their relative energy. The analysis method is discussed with the example of the pulse pattern shown in Figure 1b. We assume it consists of 1 ms pulses with a duty cycle of 90% and is repeated every 100 ms (i.e. 109 times within T_2 if $\alpha = 5.01$ mrad). The emission needs to be analyzed both in terms of actual pulses as well as in terms of pulse groups:

- The AEL is calculated using the actual pulse duration of 1 ms (t = 1 ms; also used for α_{max} and C_6) and N in this case equals 218 (the "partial N" of each pattern is 2)
- the AEL is calculated using an effective pulse duration that englobes the entire pattern (t = 5.4 ms) and N is in this case equal or lower than 109 (109 if all patterns are identical in terms of energy within T_2)

The investigation of irregular groups (i.e. pulse patterns where the groups have different duration) is not addressed in this study since it is equivalent to dealing with varying pulse durations within the emission. This subject shall be discussed in a future publication.

The key argument to justify the "partial N" approach is that thermally induced injury is highly non-linear with temperature, i.e. a relatively small reduction in temperature results in a very large reduction in the relative hazard (expressed mathematically by the Arrhenius integral) as discussed in reference [7]. The temperature increase in the tissue is directly proportional to the power emitted during the pulse. Consequently, a pulse with half the peak power of the pulse with the maximum peak power results in half the temperature increase as compared to the large pulse. As thermal injury is extremely non-linear, the pulses with the lower temperature rise contribute very little to the hazard as compared to the higher pulses, as was discussed in more detail in reference [7]. In view of this mechanism, it is straightforward to conclude that the analysis method of "partial N" as described above results in a conservative analysis, i.e. in a reduction factor C_5 that should be smaller as compared to the factor that is necessary in terms of comparison of AEL to injury threshold. In order to validate this general conclusion, a large number of emission patterns were analyzed and the injury threshold predicted by a computer model was compared to the "partial N" rule, as discussed in the subsequent sections.

Finally, while the normative scope of IEC 60825-1 is product classification on the basis of the accessible emission (AE) and accessible emission limits (AEL) for the different classes, the underlying basis of the AELs for Class 1 and Class 2 are the maximum permissible exposure limits (MPE) for the eye. For the same evaluation duration (emission duration for AEL, exposure duration for MPE) and for the same wavelength and retinal spot size, the numerical values for the AELs are the same as for the MPE when the MPE is expressed as "energy through aperture" (in Edition 3 of IEC 60825-1, MPE values are presented both in terms of radiant exposure as well as in terms of energy through aperture). In the following, for the comparison of injury thresholds against limits, we will be referring to MPEs in terms of "energy through aperture", but the discussion applies also to the analysis based on AEL for Class 1.

Materials and methods

A computer model that is validated against in-vivo non-human primate experiments [8] was used to predict thermally induced injury thresholds of the retina for a series of irregular pulse trains. The injury thresholds were then compared to maximum permissible exposures (MPE) according to Annex A of IEC 60825-1 which is equivalent to the classification rules of IEC 60825-1 Edition 3.0 (subclause 4.3.f). The parameter C_5 was determined with the concept of "partial N" as described above. The ratio of injury threshold to MPE, here referred to as reduction factor (RF) was used as the main figure of merit to evaluate the validity of the proposed rule.

The computer model has been optimized to predict injury thresholds for non-human primates, but was adapted to the human eye as follows:

- The size of a minimum visible lesion was reduced from 50 µm to 20 µm in order to account for the fact that such small lesions of the retinal pigmented epithelium might be vision impairing even if undetected by ophthalmoscopic means [9],
- the retinal image diameter was calculated by multiplying the angular subtense of the source by the focal length of the eye, i.e. optical aberrations of any kind were disregarded,
- the air equivalent focal length of the relaxed human eye was set to 16.68 mm (see Le Grand full theoretical relaxed eye in [10])

According to this model, the resulting injury threshold (THR) is a prediction of the experimental ED_{50} level, i.e. the total intraocular energy required to induce a minimum visible lesion to the retina with a probability of 50% (see [11]). It is emphasized that the above adjustments do not relate to the actual injury threshold seen in human subjects but are worst-case assumptions. Whenever exposure conditions and endpoints were comparable, injury thresholds for humans were shown to be consistently higher than for non-human primates [12]. All THR were calculated at a wavelength of 530 nm, where the RF is known to be the lowest for single pulses (results not shown).

A database of 6000 theoretical exposures was generated using the following input parameters and varying their values randomly:

- pulse duration of either 10 µs, 30 µs, 100 µs, 300 µs, 1 ms, 3 ms, 10 ms, 30 ms, 100 ms or 250 ms (constant pulse duration throughout the emission; higher probability for short pulses)
- duty cycle between 10% and 95% (higher probability for high repetition rates; 66% probability of keeping the duty cycle constant throughout the emission pattern; if variable, then 33% probability of variation between two consecutive pulses)
- number of pulses per pattern between 2 and 100; the generated pattern was randomly repeated up to 100 times and for a total emission duration of up to 10 s (pattern duty cycle up to 20%; also randomly attributed)
- peak power between 1% and 100% according to six modulation rules: random independent pulse-to-pulse variation (Fig. 2a, 30% probability), in sinusoidal form (Fig. 2b, 20% probability; up to 5 cycles per pattern), at constant level except for the last pulse which was set to 100% (Fig 2c, 20% probability), pulse-to-pulse alternation (Fig 2d, 10% probability; every other pulse at a constant level), in exponential form (Fig. 2e, 10% probability; up to 5 cycles per pattern) or without peak power modulation (not shown, 10% probability).

The database generated in this manner was considered to represent an extensive set of realistic exposure scenarios (see Figure 2) and, in view of its size and variety, to include the most hazardous ones.

For each exposure, the MPE was calculated according to the single pulse, average power and C_5 criteria (whichever was the most restrictive), only the parameter C_5 was calculated using the method referred here to as *partial N*. As suggested in the draft of the Interpretation Sheet I-SH 1, pulses of peak power below 10% of the highest peak power were neglected in the calculus of C_5.

MPE and injury thresholds were compared in terms of total energy of a given exposure, since the injury threshold is only defined for a full exposure and not for a subset of it (i.e. the MPE was scaled to give the maximum permissible total energy for a given exposure). For instance, for the case that the most restrictive MPE is obtained with Criterion 3) (i.e. $MPE_{single} \cdot C_5$), the reduction factor writes:

$$RF = \frac{THR_{emission}}{MPE_{single} \cdot C_5 \cdot N_{partial}}$$

In this equation, $N_{partial}$ is the factor that scales the limitation from permitted energy *per pulse* to the quantity of *total* energy within the emission pattern, and $THR_{emission}$ is the predicted injury threshold in terms of total energy of the considered emission pattern.

For the case that the average power criterion (averaged over a certain partial exposure duration Δt) is the most restrictive one, the RF writes instead:

$$RF = \frac{THR_{emission}}{MPE_{\Delta t} \cdot N_{partial(outside\ \Delta t)}}$$

where $MPE_{\Delta t}$ is the energy permitted within the respective partial emission duration Δt (equivalent to the power averaged over Δt and multiplied with Δt) and $N_{partial(outside\ \Delta t)}$ is the normalized sum of the energy that is outside of the averaging duration Δt, for instance equal to 3 if the energy outside of Δt is three times the energy within Δt; this factor is equal to 1 for the case that the averaging duration extends over the total emission pattern. The injury thresholds and MPEs were calculated for source angular subtense values of 5.01 mrad, 20 mrad and 50 mrad.

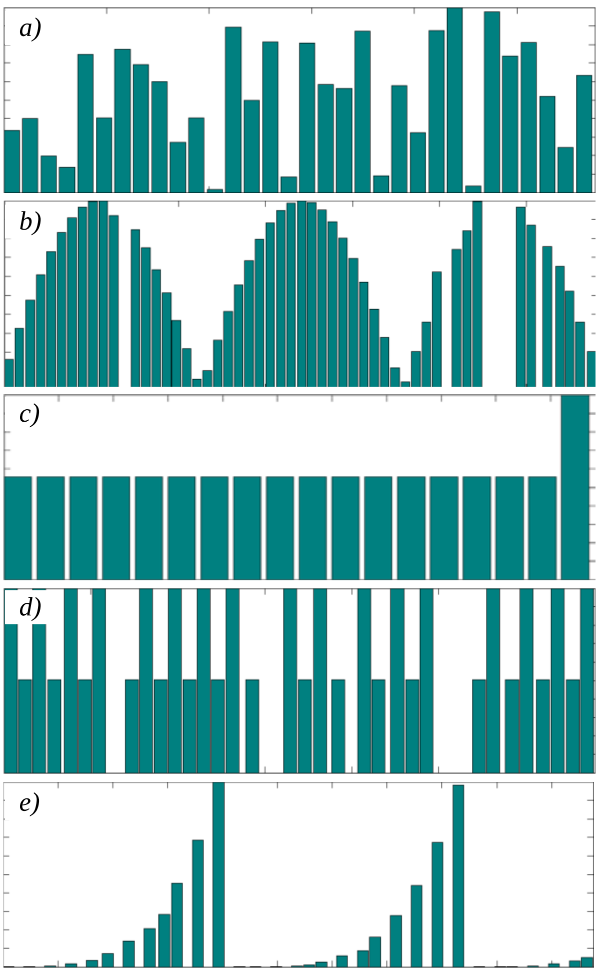

Figure 2. Excerpts of the emission database showing patterns of random (a), sinusoidal (b), pseudo-regular (c), alternating (d) and exponential (e) modulation; repeated for durations of up to 10s

Results

For the database as a whole, the most restrictive RFs were obtained for a source size of 5.01 mrad. All results reported in this section pertain therefore to a source size α = 5.01 mrad.

As compared to a more restrictive analysis counting all pulses to increase N by 1, the proposed method based on partial pulses results in the minimum reduction factor to be marginally lowered from 2.0 (for counting all pulses as 1) to 1.9 for the "partial N" method (see Table 1). However, the restrictive method is associated to much higher (overly restrictive) reduction factors in many cases as compared to the "partial N" method.

Table 1. Descriptive statistics for the database of thresholds and MPEs

Reduction factor RF	Restrictive analysis (all pulses = 1)	*Partial N* method
Minimum	2.0	1.9
Geometric mean	6.3	5.8
Std. deviation	1.1	1.0
Maximum	113	64

The average RF is not significantly different because in most cases the value of C_5 does not depend on the method, since for $N_{partial} > 40$ and $\alpha \leq \alpha_{max}$ or $N_{partial} > 625$ and $\alpha > \alpha_{max}$, the value of C_5 does not further decrease. However, the highest RF is reduced by a factor of almost 2. It also appears that the investigation of sub-groups within a pattern is not absolutely necessary in order to maintain a safety margin. The frequency response for the reduction factor is shown in Figure 3.

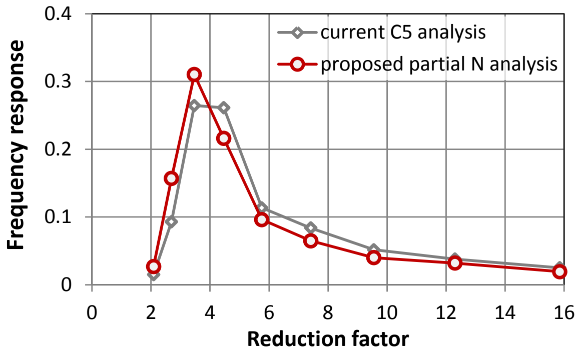

Figure 3. Distribution of the reduction factors for the conservative method (counting all pulses as 1) and the "partial N" method.

Overall, the lowest RFs are found for low N (mostly below 100), high repetition rates (above 80%) and for pattern durations in the ms range. The RFs are also not depending strongly on the pulse duration (indicating that the time dependence of AEL and the timedependent α_{max} are reflecting the injury threshold trends well). Furthermore, the lowest RFs basically do not depend on the modulation type (average RF according to cross t-tests between the six categories is not significantly different, indicating that the database was not biased towards a specific pattern type).

Finally, Figure 4 shows the lowest RF for emission durations up to 10 ms, limited by the RF associated with a single pulse. This clearly supports the concept that the patterns of varying peak power are conservatively analyzed by the "partial N" method. For exposures exceeding 10 ms, the lower limit of RFs is dominated by exposures containing a significant number of pulses with peak power lower than 10% of the maximum peak power, since they were neglected for the determination of C_5. The fact that the RF does not sink further indicates that the 10% limit is justified.

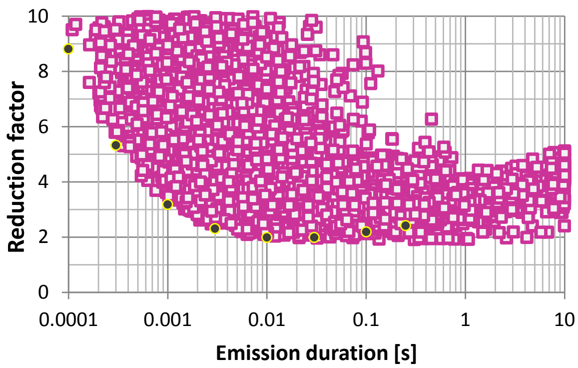

Figure 4. Reduction factor as a function of emission duration (the RF for single pulses is also shown for reference; black dots)

Summary and Conclusions

An extensive series of irregular pulse trains with pulse durations in the thermal regime (10 µs and longer) was generated in order to verify that, for each of them, the retinal threshold injury level was sufficiently above the maximum permissible exposure (MPE) for that emission. In each theoretical scenario, the level of injury threshold was calculated by means of a computer model specifically developed for that purpose. The MPE was calculated according to the methods of IEC 60825-1 Edition 3.0 including the draft I-SH 1 to determine the value of N based on the peak power of the pulse relative to the maximum peak power in the pulse train, referred to here as "partial N" method.

Although the emission patterns were generated randomly, our investigation was restricted to emissions of constant pulse duration in order to apply the evaluation method proposed in the draft I-SH 1. Since the computer model only applies to thermally-induced damage, pulse durations below 10 µs were not investigated. The comparison of the injury thresholds of the investigated patterns permits the conclusion that the "partial N" method is a viable analysis method for constant pulse durations and pulse durations in the thermal injury regime. A reduction factor equal to or greater than 2 between the predicted injury threshold and its corresponding MPE (determined with the "partial N" method) was considered as satisfactory in this regard. The non-human primate is expected to be a restrictive model for the human eye according to the literature [12].

Furthermore, our data supports that pulses with peak power levels lower than 10% of the maximum peak power during the emission can be disregarded in the evaluation of the C_5 criterion. As stated in the draft I-SH 1, this is justified for constant pulse durations. The evaluation of irregular pulse trains with both varying pulse duration and peak power should be addressed in the near future in order to enable a more general analysis method for the next Amendment of IEC 60825-1 Edition 3.0. Also the case of pulse durations in the nanosecond and short-microsecond regime, potentially leading to micro-cavity induced retinal injury, needs to be investigated within the framework of irregular pulse trains.

References

[1] International Electrotechnical Commission (2014) IEC 60825-1 Ed. 3.0: Safety of laser products – Part 1: Equipment classification and requirements

[2] ANSI Z136.1 Safe Use of Lasers (2014) Laser Institute of America

[3] Schulmeister K. (2013), The upcoming new editions of IEC 60825-1 and ANSI Z136.1 – Examples on Impact for Classification and Exposure Limits; ILSC 2013 paper #C102

[4] Schulmeister K. (2016), The new edition of the international laser product safety standard IEC 60825-1, White Paper, Seibersdorf Labor GmbH, download available at https://laser-led-lamp-safety.seibersdorf-laboratories.at/no_cache/downloads

[5] Schulmeister K. (2015), Analysis of pulsed emission under Edition 3 of IEC 60825-1; ILSC 2015 paper #202

[6] IEC TC 76, Draft Interpretation Sheet 1 for IEC 60825-1 Edition 3.0; 76/553/DC (September 2016).

[7] Schulmeister K. and Jean M. (2011), Manifestations of the strong non-linearity of thermal injury; ILSC 2011Paper # 901, p. 201 – 204.

[8] Jean M. & Schulmeister K. (2013) Validation of a computer model to predict laser induced thermal injury thresholds of the retina, ILSC 2013 paper #1002

[9] Lund D.J., Edsall P. & Stuck B.E. (2001) Ocular hazards of Q-switched blue wavelength lasers, Proc. of SPIE 4246, 44-53

[10] Atchison D.A. & Smith G. (2000) Optics of the Human Eye, Butterworth-Heinemann: Edinburgh

[11] Sliney D.H., Mellerio J., Gabel V.P. & Schulmeister K. (2002) What is the meaning of threshold in laser injury experiments? Health Phys 82:3

[12] Stuck B.E. (1984) Ocular susceptibility to laser radiation: human vs. rhesus monkey, Chapter 4 in Handbook of laser bioeffects assessment – Volume 1 – Bioeffects data, Letterman Army Institute of Research, San Francisco CA