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Karl Schulmeister

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Author: *Schulmeister K*

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ANALYSIS OF PULSED EMISSION UNDER EDITION 3 OF IEC 60825-1

Paper #202

Karl Schulmeister

Seibersdorf Laboratories; Laser, LED and Lamp Safety Test House and Consulting;
2444 Seibersdorf, Austria

Abstract

In IEC 60825-1 Edition 3, the rules for analysis of multiple pulses in the retinal hazard region were amended significantly, in most cases permitting higher emissions, and in some cases being more restrictive than Edition 2. Some of the specified requirements and changes should be complemented with additional information, which is currently developed by IEC TC 76, to be published as an Interpretation Sheet. In this paper, a list of items is presented which should lend themselves to be considered by IEC TC 76 for this Interpretation Sheet.

Introduction

The changes of IEC 60825-1 Edition 3 [1] with respect to earlier editions were reviewed in an ILSC 2013 paper [2]. The present paper relates to the rules laid down in Subclause 4.3 f) which describe how classification of products with pulsed emission (or scanned emission that leads to a pulsed accessible emission pattern) is to be performed. As in previous editions, three criteria are given which have to be considered in parallel, i.e. it depends on the product 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 mainly relates to the factor C_5 and therefore to limits that can be associated with retinal thermal hazards.

1) 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) The accessible emission expressed as average power (averaged over a certain time period) has to be below the AEL applicable for that averaging duration, while 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 is shown further below 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.
3) Criterion 3) calls for the application of C_5 to reduce the single pulse AEL, i.e. a more restrictive version of Criterion 1 (or the same for the case where $C_5 = 1$). While the current standard wording, Criterion 3) appears as not necessary to apply C_5 for the case of pulse *groups*, on 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. For this analysis, a group of pulses is considered as one thermally effective pulse and N is the number of pulse groups within the applicable duration (such as T_2), and the accessible emission is derived as energy of pulse group (i.e. integrated over the pulse group), and the AEL is calculated for the pulse group duration.

The criteria that were given in Edition 1.2 and Edition 2 of the standard were for instance discussed in reference [3].

A frequent question is why the total-on-time-pulse (TOTP) criterion is no longer part of Edition 3. The answer is that for most cases, the TOTP would be needlessly restrictive, as C_5 in edition 3, when it is not equal to 1, is limited to some maximum reduction such as 0,4 or 0,2. However, the basis of the equivalence (see for instance [3]) is that $C5=N^{-0,25}$ and not limited. At the same time, in Edition 3, the accessible emission is smaller than in Edition 3 when the apparent source is larger than α_{max} but α_{max} is time dependent and would be determined at TOT for the TOTP, which results in a larger α_{max} (being more restrictive as it increases the AE) than for the rule based on single pulse duration. Thus, applying the TOTP would result in a higher accessible emission as necessary. The regimes where the TOTP still could be used and would be fully equivalent with the rules of Edition 3 are therefore:

- Pulse durations longer than T_i
- Apparent source between 5 mrad and α_{max} determined for the pulse duration.
- Number of pulses not more than 40

This is a relatively small parameter space and therefore it was decided not to include the TOTP as an alternative treatment for Edition 3. It could be considered to adjust the TOTP method to the current rules to extend the range where it is applicable (as an alternative to the C_5 expression), such as using α_{max} of the single pulse for the determination of the AE, and limiting the TOT to a maximum of 40 pulses, but it would have to be considered what the limitations are for this approach. For instance, the TOTP could err on the unsafe side by adding pulses with low energy per pulse to the pulse train, making it less restrictive by adding pulses (that add to the TOT but not adding a lot of energy when the peak power is low) and this would be a case where the TOTP should not be applied.

Equivalence of single pulse and average power criterion

It is shown in the following that Criterion 2 (average power) is in effect a form of a single pulse criterion, understanding the averaging duration as the duration of an "effective pulse":

For Criterion 2, the average power P_{av}, averaged over all applicable averaging durations T_{av}, needs to be less than the AEL, expressed as power value, applicable for that averaging duration $AEL_P(T_{av})$. Contrary to Criterion 3, there is no factor $C_5 = N^{-0,25}$ applied for Criterion 2, however.

The analysis expressed as average power values is equivalent to an "energy" analysis and considering those pulses within the averaging duration as one effective pulse. This can be seen when it is considered that average power is nothing else than the energy integrated over the averaging period and then dividing that total energy within the averaging duration by the averaging duration.

P_{av} = Sum of $Q(T_{av}) / T_{av}$

Consequently, the average power criterion can also be expressed as:

The energy added up over all applicable integration durations T_{av} needs to be below the $AEL_Q(T_{av})$ calculated for T_{av} where the AEL is expressed as energy value.

Expressed in terms of average power, Criterion 2 can be written as:

$AEL_P(T_{av}) > P_{av}$ or replacing P_{av}

$AEL_P(T_{av})$ > sum of Q over T_{av} / T_{av}

This average power rule can thus be expressed in an equivalent way terms of energy values as (by multiplying above formula with T_{av})

$AEL_Q(T_{av})$ > sum of Q over T_{av}

Thus, comparing the average power, averaged over T_{av} with the AEL expressed as power and determined for T_{av} is equivalent to comparing the energy within T_{av} with the AEL expressed as energy as determined for T_{av}, since

$AEL_P(T_{av}) = AEL_Q(T_{av}) / T_{av}$

In that sense, Criterion 1 and Criterion 2 can both together be understood as the simple and basic requirement that the accessible emission shall not exceed the respective AEL for any emission duration. The only difference between Criterion 1 and Criterion 2 that prevents to say that Criterion 2 is identical with Criterion 1 when the integration duration is set as the pulse duration of the single pulse, is that for Criterion 2, the energy is integrated over a sharply defined integration window (i.e. energy outside of that integration window is set to zero) and the AEL is determined for the duration of the integration window. For Criterion 1 (and also Criterion 3, by the way), however (as well as for the basic single pulse criterion), the duration for which the AEL is determined is defined as to be based on FWHM criteria and the energy that is considered as accessible emission is the total energy per pulse, not just the part that is within the FWHM.

It is also interesting to note that Criterion 3, which calls for multiplying the single pulse AEL with C_5 is an extension of Criterion 1. When Criterion 3 is also applied to pulse groups (which is a necessary additional application that is currently not specifically required in Edition 3 but based on physical basics is necessary), this is similar to an extension of Criterion 2, where C_5 is applied to the AEL expressed as energy that applies to one pulse group and C_5 is determined for the number of pulse groups (again Criterion 3 applied to pulse groups might not exactly the same as applying C_5 to the average power rule, due to the differences between FWHM and integration duration mentioned above as difference between Criterion 1 and 2). However, in the development of the interpretation sheet regarding the application of C_5 to pulse groups, it might be possible to specify that in a way that facilitates the analysis in the sense of extending the analysis of the average power that needs to be performed for irregular pulses for different averaging durations anyway to include C_5.

While analysis according to IEC 60825-1 Edition 2 was somewhat simpler as it was generally the case that Criterion 3 was always more restrictive than Criterion 1 and 2 (or for repetition rates above $1/T_i$ Criterion 2 was equivalent to Criterion 3), for Edition 3 it is in many cases less restrictive but at the same time more complex. Depending on the emission pattern and source size, different Criteria can be the limiting one, as theoretically analysed in Reference [4].

Rules for C_5

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.

The biophysical background of the two different sets of rules, one for pulse durations less than T_i (i.e. 5 µs or 13 µs, depending on wavelength range) and one for longer than T_i is that for longer pulse durations, the injury mechanism is thermal bulk heating of the RPE, while for the shorter pulse duration regime, the injury mechanism is micro-cavitation, i.e. super heating of melanin granules within the RPE. These are quite different damage mechanisms and also the background regarding additivity of pulses is different. There is some discussion if it is necessary to even apply a $C_5 <$ 1 in the micro-cavitation regime at all, and ANSI Z136.1 (2014) for instance only requires lowering the single pulse limit for exposure were the eye is immobilized or the pupil is dilated (see also discussion in reference [5]).

Bioeffect backgrounds are not discussed in this paper, but it is noted that the C_5 rules for pulse durations above T_i could be called the "thermal C_5" and the C_5 rules for pulse durations less than T_i could be referred to as the "micro-cavitation C_5", or µ-cav for short.

List of Potential Items for Interpretation Sheet

Introduction

The following text relates to Criterion 3) of Subclause 4.3 f) which is the criterion where the factor C_5 is applied to the single pulse AEL. The text features issues where the author has noticed in discussions with standardisation expert colleagues and clients that some clarifying text would be advantageous, and IEC TC 76 has started to work on an Interpretation Sheet to be issued by IEC in the second half of 2015. The following text should not be considered as a draft for the interpretation sheet, however.

1) Value of α not limited to α_{max}

The angular subtense of the apparent source α is a parameter in the criteria that determine what value for C_5 to apply. For instance the following expressions are used

"For $\alpha > \alpha_{max}$" and

"Unless $\alpha > 100$ mrad"

Comment

For the determination of α as a parameter in these criteria (contrary to α as parameter of C_6), the value of α is not limited to α_{max} (this also applies for oblong sources where α is the arithmetic mean of the angular subtense in each dimension). This is to a degree obvious as otherwise, the above conditions would never be fulfilled, but it might be some cause for confusion. Consequently, for one given image of the apparent source, the value of α used for the above conditions could well be a different (larger) value as determined when α is limited (for an oblong source in each dimension before averaging) to α_{max}.

2) Varying pulse durations, constant peak power

Depending on the angular subtense of the apparent source, it can be the case that the value of C_5 (and therefore $AEL_{s.p.train}$ that limits the energy per pulse) is more restrictive for pulses with pulse durations less than T_i than for pulses with durations longer than T_i, particularly for instance where the “thermal” $C_5 = 1$.

Comment

For the case of varying pulse duration within a pulse train, if the accessible emission for the longest pulse is below the applicable AEL, then it can be assumed for the analysis that shorter pulses <u>with the same or lower peak power</u> are not more critical. This especially applies to the case where the longer pulses are longer than Ti and they are below the AEL of a given class. Pulses shorter than T_i, <u>if they have the same or a smaller peak power as the longer pulse</u>, also satisfy the requirement that the accessible emission is below the accessible emission limit for the respective class, even though when applying the rules for pulse durations less than T_i, the AE would exceed the AEL applicable to the regime of pulse durations less than T_i.

Example

For instance, consider that the accessible emission consists of pulses with 7 µs duration and with 3 µs duration. For the case of $\alpha \leq 5$ mrad, Criterion 3 for $t>T_i$, $C_5=1{,}0$ and for $t \leq T_i$, C_5 can become as low as 0,4. The AE of a single pulse with t = 7 µs is below the AEL for that pulse duration. If the t = 3 µs pulses do not have a higher peak power as the 7 µs pulses, it cannot be the case that a shorter pulse with the same peak power is more restrictive than a longer one and the 3 µs pulse can therefore also assumed to comply with the requirement that the accessible emission is below the accessible emission limit even though it might not satisfy $AEL_{s.p.train} = AEL_{single} \times C_5$ where C_5 could be equal to 0,4.

That for a given peak power, the emission cannot become more hazardous when the pulse duration is becoming shorter is a basic principle and particularly applies to the transition from the thermal to the micro-cavitation regime: when the peak power for a longer pulse is not sufficient to induce thermal bulk heating and damage, it can also not induce temperatures in the melanosome to become hazardous (as otherwise the injury mechanism at the longer pulse durations would also have to be based on micro-caviation).

3) Using a square aperture for analysis

In some cases, such as scanned laser beams, the usage of a circular aperture to determine the accessible emission creates very complex pulse patterns. The pattern of accessible emission is simpler when a square aperture is used. Due to the breakpoints in terms of pulse duration with step functions in the value of C_5, it might not be apparent that the usage of a square aperture is acceptable as simplified worst case analysis.

Comment

When a circular aperture is used, and the emission is scanned, a scan that passes the circular aperture outside of the center of the aperture will result in a shorter pulse duration (the chord of the circle is less than 7 mm long) as compared to a scan across the center of the aperture where the chord is equal to the diameter and equals 7 mm. This is a situation where Item 2) can be applied and when the scan through the center of the aperture satisfies the applicable AEL for the longer pulse duration, also scans across the aperture at other positions can be assumed to comply. With the same justification, analysis as performed with a square aperture with 7 mm side length (determination of accessible emission and pulse duration) can be assumed to be equal or less restrictive than a circular aperture and is therefore a valid analysis.

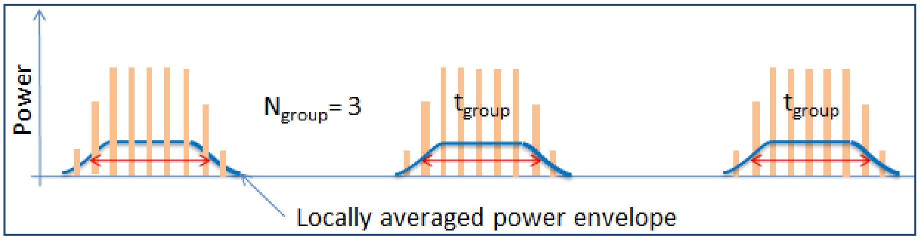
4) Groups of pulses

It is not stated how Criterion 3 is to be applied for groups of pulses when the pulse group is longer than T_i.

Comment

For the application of Criterion 3), based on simple biophysical principles, pulse groups are to be considered as effective pulses, provided that the group duration is longer than 5 µs for wavelengths < 1050 nm and longer than 13 µs for wavelengths 1050 nm $\leq \lambda <$ 1400 nm. This can be easily seen that this is necessary as if the temporal spacing between the pulses within a pulse group is relatively short so that there is no effective cooling between the individual pulses (and for extended sources the cooling is relatively “slow”), then the whole group thermally w.r.t. the temperature is identical to one effective pulse with corresponding duration and energy.

Consequently, the value of AEL_{single} is determined for the corresponding duration t_{group} of the pulse group. The duration of the pulse group is determined by considering an envelope of the individual pulses that is defined by the peak power values of the pulses that make the pulse group, and applying the FWHM definition for the duration of the group of pulses (see figure below). To facilitate the analysis, it might be possible to justify to use the overall duration of the pulse group as pulse group duration rather than to have to use the FWHM of the locally averaged power levels as shown in the figure. This would permit using the same analysis as for the average power criterion where different integration durations have to be applied (see discussion at the beginning of the paper).



For the analysis of pulse groups with group durations longer than T_i, the rules regarding C_5 as given for $t > T_i$ apply, using the pulse group duration for t. AEL_{single} is compared against the accessible emission that applies to the group of pulses, i.e. the sum of the pulse energies that make up the pulse group is used as accessible emission. For the determination of C_5, N is the number of pulse groups N_{group} within the applicable evaluation duration, so that N_{group} is correspondingly smaller than the number of pulses overall; for instance if one group consists of 10 pulses, then N_{group} is 1/10 of the number of pulses within T_2 of 0.25 s depending on the intended class.

Application of C5 to pulse groups could under Edition 2 never be more restrictive than application to the actual number of pulses, as can be easily shown mathematically for the simple example of a pulse group of 2 pulses which are assumed to be spaced closely together, so that the duration of the pulse group equals, assuming rectangular pulse profiles: 2 x pulse duration + spacing: the energy per pulse group is twice the energy per pulse, but the AEL that applies to the pulse group is always (due to the spacing between the pulses) larger for the pulse group, i.e. the group has a factor of "$spacing^{0,75}$" higher AEL values. Under Edition 3, due to the limitation of C_5 to N=40 or N=625, it could be the case that pulse groups are more restrictive. Another case is where the individual pulse duration is less than 5 µs and for Class 2 time bases then the µ-cav C_5=1, i.e. no reduction for the individual pulses, but the pulse group could have a group duration of longer than 5 µs so that C_5 (if the angular subtense is larger than 5 mrad) would apply to the pulse group. Especially (but not only) in this latter case and when the group duration is below 18 µs (the value of T_i in Edition 2), the analysis could be more restrictive than Edition 2, as the single pulse AEL for pulse durations below 18 µs was reduced for Edition 3 (being based on insufficient safety factors in the nanosecond regime). In the regime between 5 µs and 18 µs there is actually a relatively large safety margin between injury thresholds and AEL (see for instance 3 µs data by Zuclich et al. [6]) so that following future analysis of bioeffect data, it might be possible in future Amendments of the standard (and of the respective ICNIRP guidelines) to specify that for application of C_5 < 1 (i.e. for apparent sources larger than 5 mrad), and group durations between 5 µs and 18 µs, the AEL applicable for 18 µs can be used rather than the AEL of the actual pulse group duration. If this can be justified, it would not only hold for pulse groups in that regime but also for single pulses, and in effect would mean that the single pulse AEL is kept constant at the 18 µs level for pulse durations to some breakpoint such as 5 µs where there would be a step of 2.5. However, due to the scarcity of bioeffect data, and the necessity to consider several dependencies, it is be difficult to justify such an amendment or interpretation at this point in time.

5) Intermediate Oblong Sources

The applicable value of C_5 depends on the value of α. It is not stated if both dimensions of the apparent source need to satisfy a given criterion or if the arithmetic mean is to be used. This item applies to the criteria:

For $\alpha \leq 5$ mrad:

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

For $\alpha > 5\ \alpha_{max}$:

The criterion "unless α > 100 mrad" needs to be treated separately and is discussed in Item 6)

Comment

For the determination of α for intermediate oblong sources, the arithmetic mean is applied, as is generally defined (see 4.3 d).

Example

For instance, this means that it is not necessary that both dimensions need to be smaller than 5 mrad in order for that C_5=1 applies, it is sufficient that the arithmetic mean is smaller than 5 mrad (which is for instance satisfied by a rectangular source with 1,5 mrad width and 8 mrad length).

6) Large Oblong Sources

The criterion "Unless α > 100 mrad where C_5 =1,0 in all cases" is discussed in this Item.

Comment

For this criterion to apply, both dimensions of the apparent source need to be larger than 100 mrad, not just the arithmetic mean.

7) Simplified Analysis

For pulse durations longer then T_i, the value of C_5 is smaller (more restrictive) for angular subtense values α larger than 5 mrad as compared to smaller values of α, such as for small sources (α = 1,5 mrad) which, however, is the basis of the simplified analysis. It is therefore not obvious if the simplified analysis still applies for the case that the source is actually extended (i.e. the question could be if it is necessary to apply the extended method where C_6> 1, i.e. less restrictive, but C_5 < 1, i.e. more restrictive than for the assumptions of the simplified method.

Comment

It should be applicable to make use of the simplified restrictive assumption of α = 1,5 mrad (C_6 = 1, C_5 = 1) even for the case that the angular subtense of the source is larger than 5 mrad, where C_5 could be smaller than 1. This means it is not necessary to measure α and to show that α < 5 mrad in order to apply C_6 = 1 and C_5 = 1 for a simplified analysis.

8) Blurred Image of Apparent Source

For the extended analysis, for a given evaluation position in the beam, the accommodation state of the eye is to be varied to determine the angular subtense of the apparent source. The criterion for the determination of the most critical accommodation state is to maximise the ratio of accessible emission over AEL.

Comment

It is not necessary to include C_5 in the AEL for the image analysis to determine the value of α for Criterion 3, i.e. it is sufficient to determine the most critical image of the apparent source (most critical ratio of AE/AEL) with the AEL is for a single pulse.

Example

This also means that, for instance for a circular diffuser as the apparent source, where it is the accommodation to the diffusor which produces the smallest value of α and the most critical ratio of AE/AEL, to accommodate in front or behind the diffusor, which results in a larger angular subtense of the image, cannot be more restrictive or critical (which it could be if Criterion 3 would be applied to determine the most critical ratio when the diffusor subtends and angular subtense of 4 mrad and when it is blurred could subtend an angle of 6 mrad).

Concluding Remarks

Edition 3 of IEC 60825-1, based on the 2013 revision of the ICNIRP guidelines [7], introduced some significant amendments w.r.t. analysis of multiple pulses or scanned emission. Some of the rules appear counterintuitive, such as that an apparent source that is somewhat larger than 5 mrad can have a significantly lower AEL than a 5mrad apparent source; also there is a step function at T_i (i.e. 5 µs for wavelengths less than 1050 nm).

Obviously, the retinal injury thresholds do not feature such step functions. However, a set of limits and rules that would smoothly transition from one domain into the next (such as from thermally induced injury into the micro-cavitation domain) would mean that the rules are even more complex, as well as that there might not be sufficiently dense bioeffect threshold data available for all parameter variations such as threshold as function of pulse duration, repetition rate, number of pulses, source size and wavelength, all of which need to be considered in terms of dependencies.

It is emphasised that most lasers are collimated lasers where for pulse durations longer than 5 µs by setting C_5 = 1 the analysis was both greatly simplified as well as made significantly less restrictive.

Some questions on how to apply the amended rules for extended sources remain and this paper is attempt to discuss some of them, which could form part of a planned interpretation sheet for IEC 60825-1.

For the case of application of C_5 to pulse groups with groups durations between 5 µs and 18 µs it is unfortunate that this could have rather restrictive results, possibly even more restrictive than Edition 2, but at the moment, without further bioeffects data available it is difficult to recommend a less restrictive analysis and make sure that safety margins are sufficiently large for all parameter combinations.

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Meet the Author

Karl Schulmeister, PhD, is a consultant on laser and broadband radiation safety at the Seibersdorf Laboratories, where also a specialized accredited test house is operated. Karl is a member of the ICNIRP Scientific Expert Group as well as of ANSI ASC Z136 TSC-1 (Bioeffects). He served as project leader for the development of IEC 60825-1 Edition 3. The research in his group over the last eight years concentrated on thermally induced injury that also provided the scientific background for amending the spot size dependence and multiple pulse rules of the retinal thermal limits.