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ANALYSIS METHOD FOR THE DETERMINATION OF THE APPARENT SOURCE SIZE IN BROADBAND RADIATION

Paper #P106

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Abstract

The accessible emission limits (AEL) for the retinal thermal hazard as specified in the international standard series IEC 62471 for photobiological safety of lamps and lamp systems depends on the angular subtense of the apparent source α. No method is specified how to determine α for complex sources such as LED arrays or image projectors. Currently, the peak radiance has to be compared against the AEL determined with largest value of α that can be associated to the apparent source, often leading to overly restrictive results. A method was developed for determining the size of the apparent source and permitting averaging radiance over a certain field of view, with the aim of producing appropriate safety margins for any possible irradiance profile. It was validated against more than 250 exposure scenarios by means of a computer model for laser-induced retinal injury to ensure that the injury threshold level is in no instance lower than 1.5 times the AEL. The proposed method for complex apparent sources is up to 10 times less conservative than using the outer edge for the determination of α and the peak radiance.

Introduction

Exposure limits that ensure protection against retinal thermal injury are promulgated by ICNIRP for broadband incoherent radiation [1]. These ICNIRP guidelines are adopted both for legally binding *exposure* limit values at the workplace in Europe [2], but also product safety *emission* limits are derived and specified in product safety standards developed and issued by the IEC for classification of lamps and products emitting optical broadband radiation [3]. Here, we limit ourselves to accessible emission limits referred to as AEL (although the term *emission limit* is used throughout [3], we adopt here the acronym AEL for *accessible emission limit* as in Part 5 of the IEC 62471 for image projectors [4]). The AEL for Risk Group 2 in IEC 62471-5 (currently at the CDV stage, with approval to be issued as FDIS) is equal to the updated ICNIRP exposure limit published in 2013, which is also the basis for updating IEC 62471, which will become IEC 62471-1.

For the retinal thermal hazard, the AEL depend on the parameter angular subtense of the apparent source with the symbol α, equivalent to the effective diameter of the retinal irradiance profile [5]. More exactly, the AEL is given as AEL(α^{-1}) in units of radiance, i.e. inversely proportional to the source size. The exact details of the dosimetry and biophysical background are not discussed here but are available in other publications [6, 7, 8, 9]. We only note that radiance is for a given pupil diameter directly related to retinal irradiance and is the ideal dosimetric concept for extended retinal images.

It has to be appreciated that the parameter α, scaling the AEL for the retinal thermal hazard, is identified as the actual diameter of the irradiance profile only for a circular top-hat image. For other, complex profiles, a three dimensional information – namely the local irradiance as function of x- and y-axes – needs to be condensed into one single representative figure – namely α – for which there is no generally applicable method specified in IEC 62471, particularly for the case of disjoint irradiance profiles such as LED arrays. In the absence of specific guidance, it is necessary to apply a restrictive method, which is to determine α from the outer edge of the entire profile such as the array (i.e. the largest value of α) and to use the peak radiance of the profile (i.e. radiance averaged over a field-of-view of 5 mrad or 11 mrad for pulsed and cw emission, respectively). When the distance between the elements of the array is large enough, it can be argued that this method is likely to be needlessly restrictive (α being derived from the outer edge of the array, resulting in a relatively smaller AEL) because the LEDs are imaged far apart from each other onto the retina while the subsequent thermal injury does not results from the ensemble but from a subset of the profile. In such case, it might be appropriate to determine α from a subset of the image or from one single LED only (resulting in a higher AEL) and/or averaging the radiance over an area larger than one element (resulting in a lower accessible emission that is compared against the AEL). It is emphasized that the proposed method, the application of which may require image analysis, is optional, i.e. it is always possible to apply the more simple conservative method or even simply assume that α is equal to α_{max}.

These proceedings describe the method proposed for determining α for irregular sources and averaging the radiance accordingly. Validation data provided means of a computer model for predicting retinal injury thresholds (THR) shows that, for all investigated exposure scenarios, the ratios of THR to AEL are in the targeted range of values from the point of view of safety, i.e. neither too large (over-restrictive AEL) nor too small (unsafe AEL). Finally, the improvement over the current restrictive method is emphasized and limitations are discussed.

Rationale

In the remainder of the paper, we refer for simplicity to retinal irradiance rather than radiance and note that radiance and irradiance are simply proportional to each another by multiplication with the solid angle subtended by the pupil of the eye, the diameter of which is assumed to be 7 mm. Classification according to IEC 62471 in the retinal thermal hazard region requires the determination of the angular subtense of the apparent source α. It is currently defined by the 50% points of the irradiance profile and its value is limited by lower and upper limits: α_{min} and time-dependent α_{max}, respectively. In that regard, α is currently identified as the “diameter” of the area, in case the profile exhibits axial symmetry, or as the arithmetic mean of length and width of the circumscribed rectangle (smallest rectangle containing the 50% contour of the irradiance profile) in any other case (limiting each dimension first to α_{min} and α_{max}).

For the determination of the risk group of the lamp or lamp system, the AEL of a given risk group is compared against the radiance that is determined for that product for a given reference distance and averaging field of view (FOV). This quantity that is compared against the AEL is referred to here as the accessible emission, or AE. Thus classification to a certain risk group requires AE < AEL. If for instance the AE is reduced by introducing a larger averaging FOV by a factor of 2 and the AEL is also reduced by a factor of 2 due to an increased value of α, the ratio is the same and in terms of classification there is no difference between the two cases. In the same way, classification can be made less restrictive by reducing the AE following averaging of radiance over some larger FOV, or by increasing the AEL by reducing the value of α or a combination of both.

Proposed Method

Basic Concept and Example

The proposed method is not based on the 50% points of the irradiance profile but on an image analysis method where the searched area is systematically varied in position and size until the most restrictive ratio of AE to AEL is identified. Potential candidates for the critical integration area A, source size α, AE and AEL are denoted by using the index *i*. Each searched area Ai is associated with a value of α_i and therefore AE_i and AEL_i. The solution of the image analysis is the candidate producing the highest ratio AE_i/AEL_i. The classification procedure then sets AE as an average radiance against the AEL where α is the angular subtense associated to the critical area.

The method, using a rectangular analysis area, is exemplified with two square elements as the retinal irradiance pattern, such as could be formed by the bare chip of two LEDs. The length of one side element is *a* and the distance of the two elements is assumed to be a variable *b*, where the value of both *a* and *b* is between α_{min} and α_{max}. Each element has the same radiance L and therefore retinal image irradiance E, which can be calculated by dividing the power P by the area of one element a^2. Thus choosing the first analysis area A_1 to be equal to the area of one element, results in a value for AE/AEL of $P/a^2 \cdot a = P/a$. Averaging over both elements results in averaging over the rectangle that has an area $A_2 = a \cdot (2a+b)$ and $AE_2 = 2P/A_2$. The parameter α for this analysis rectangle is equal to (3a+b)/2, the inverse of which can be used as relative value for AEL_2. Comparing AE_2/AEL_2 with AE_1/AEL_1 shows that averaging over both elements produces the largest AE/AEL ratio and therefore is the solution of the image analysis – irrespective of the distance between the elements. For instance, setting b=a, $AE_2/AEL_2 = 4P/3a$; 5P/4a for b=2a. In this example, the proposed method results in the same value of α as the current restrictive method, however the accessible emission is correspondingly smaller as it is averaged over the larger image area. For b=2a, the average radiance is half of the radiance of one element. The validation process that is described further below showed that, in order to maintain a sufficient safety margin for any image pattern, it is necessary to increase the AE by a factor of 1.3 and it is also necessary to systematically investigate circular averaging areas in addition to rectangular averaging areas (FOV) and apply the more restrictive result (overall maximum ratio of AE/AEL).

Significant efforts were invested in searching for a simpler, more direct method but all these other methods failed at keeping a minimum safety margin. For completeness it should also be mentioned that the solution of the image analysis is not necessarily representative of the injury pattern or always intuitive, and should be seen just a method to obtain the AE and α which is for most complex cases significantly less restrictive than the current method.

Analysis Method

The ratio of AE to AEL shall first be maximized where AE is defined as an average radiance, averaged over an area A_i. Each analysis area is also characterized by the angular subtense α_i. Since the value of α is a priori unknown, maximizing the ratio of AE to AEL requires varying the shape, size and position of the integration area across the entire image and evaluating the ratio in all possible situations. The 1st edition of IEC 62471 as well as the draft 2nd edition, i.e. IEC 62471-1 specified 1.7 mrad for pulsed emission and 5 mrad for cw emission as the minimum angle of acceptance; while IEC 62471-5 specifies 5 mrad and 11 mrad, respectively (based on the requirement that if such an averaging angle is used, α is not permitted to be smaller than the averaging angle). The value of 11 mrad was also recommended by ICNIRP in the 2013 revision, and there are several factors and arguments that played a role in recommending this value, including that lamps can only represent a retinal thermal hazard at close distance and when they are relatively large sources and that if they feature hotspots these would not be very small. However, these assumptions might no longer apply for the case of laser based systems which can be as small as 5 mrad at 20 cm. At this point in time, we would recommend not to average the irradiance over an angle of acceptance of less than 5 mrad, both for pulsed and cw emissions.

Solving the optimization problem requires investigating:

- the entire range of integration areas within the limits of α_{min} and α_{max}
- <u>both</u> circular and rectangular integration areas, where α is the diameter of the area of interest in the first case and the arithmetic mean of length and width in the latter case (the limits for α apply to each dimension independently, not to the mean).
- the entire image in a systematic manner, not only regions around or containing the position of peak irradiance, where orienting the rectangular integration area in the principal axes of the image is recommended for the purpose of optimization

The solution of the maximization process gives directly the solution for α and therefore the AEL. The critical averaging area (size, position and shape) allows calculating or measuring the average radiance to be used as AE, where an additional factor of 1.3 is needed to maintain a sufficiently large safety margin. Due to the increase of the AE by a factor of 1.3, the proposed method can in some cases be more restrictive than the current method of taking the outer edge of the image profile to determine a and to take the radiance averaged over some angle of acceptance. Consequently, the currently applicable method can be used in complement to the new method as described in Figure 1.

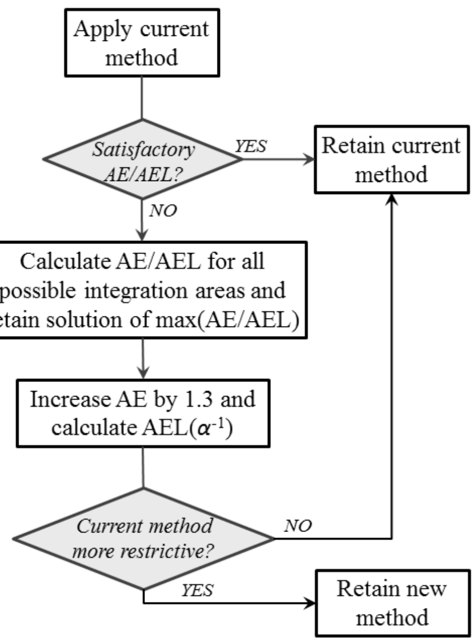

Figure 1. Steps to follow for determining accessible emission and accessible emission limit in the case of a complex irradiance profile

Validation

Since the proposed method can lead to a smaller value for α as compared to the current method (50% outer edge points of the irradiance profile), hence to higher AEL level, a validation process is required so as to ensure that the method cannot produce unsafe results, i.e. where the permitted AE were to be too close to the injury threshold level because of excessive averaging effects.

To this end, a computer model was used to predict laser-induced injury thresholds of the Rhesus monkey retina [11]. The computer model, validated against all applicable non-human primate in-vivo data was adjusted to the properties of the human eye as follows:

- the size of a threshold lesion (in the sense of a minimum visible lesion) to the retinal pigment epithelium was reduced from 50 µm to 20 µm because it cannot be ruled out that such small lesions are vision impairing when located in the central portion of the retina (fovea) although such small lesions are not detected by ophthalmoscopic means [12].
- the minimum retinal spot size was set to 25 µm; see discussion in [7]
- the air equivalent focal length of the relaxed human eye was set to 16.68 mm (see Le Grand full theoretical relaxed eye in [13])

According to this model, the resulting injury threshold (THR) for a given wavelength, irradiance profile and exposure duration is a prediction of the experimental ED50 level, i.e. the total intraocular energy required to induce a minimum visible lesion to the retina with a probability of 50% [14]. It is emphasized that the predictions are still based on data obtained with non-human primate models and the above adjustments do not relate to the actual injury threshold. Nevertheless, where exposure conditions and endpoints were comparable, injury thresholds for humans were consistently higher than for non-human primates [15].

Besides the basic circular Top-hat profile, 233 THR were calculated for the purpose of validation for various image patterns and exposure scenarios (varying exposure duration and wavelength) representative of the thermal regime. The exposure duration was varied between 1 ms and 0.25 s, and the wavelength was either 530 nm or 1060 nm. The irradiance profiles investigated here are described in Table 1 (characteristic structure, free parameters and their range) and illustrated in Figure 2 (one profile of each kind).

For each image, the analysis method was applied as described in the previous section to obtain the critical averaging area and the corresponding value of α used to calculate the AEL value in terms of radiance. For comparison with the predicted injury threshold, this AEL is expressed as retinal irradiance which can also be written as C/α. The reduction factor RF (or safety margin) is here defined as the ratio between injury threshold for a minimum lesion and AEL as follows:

$$RF = \frac{R(\lambda) \cdot THR \cdot 1.3 \cdot \alpha}{C}$$

where THR is the injury threshold level averaged over the integration area characterized by α. The constant C

Table 1. Properties and free parameters of the irradiance profiles (series labelled from “A” to “T”) investigated here; “unit” refers here to a square spot

	Structure type	Free parameters and range	Properties (constant)
A	Single circular top-hat	Diameter: 1,5-100 mr	-
B	Array of 3x3 units	Units: 1 to 9 Random arrangement	Spacing: 5 mr
C	Array of 3x3 units	Spacing: 0-30 mr	-
D	Array of MxN units	Size: up to 6x6 units	Spacing: 5 mr
E	Array of adjacent units	Size: 1 to 8 units Random arrangement	Side length: 5 mr
F	Single rectangular top-hat	Side length: 5-80 mr	Area: 400 mr^2
G	Three inline units	Spacing: 0-30 mr	Side length: 5 mr
H	Three parallel rectangular spots	Spacing: 0-30 mr	Size: 5x15 mr
I	Two units	Spacing: 0-25 mr	Side length: 5 mr
J	Two parallel units	Length: 10-45 mr Spacing: 1-10 mr	Width: 5 mr
K	Two arcs “horseshoes”	Radius: 1,5-20 mr Spacing: 2-10 mr	2-fold rot. symmetry, arc thickness: 5 mr
L	Circular Top-hat with hot spot	Irradiance ratio: 1:1,5 - 1:21 Spot diameter: 7-72 mr	Hot spot diameter: 6 mr
M	Rectangular Top-hat with hot spot	Irradiance ratio: 1-10	Hot spot: 5x10 mr Spot: 5x20 mr
N	Array of 3x3 units with hot spot	Irradiance ratio: 1-8	Side length: 5 mr Spacing: 1,5 mr
O	5 inline units with 2 out-of-axis units	Irradiance ratio: 1-8 Location/numbers of hot spots	Side length: 5 mr Spacing: 2,5 mr
P	Single Gaussian spot	Length (1/e): 5-25 mr	Width: 5 mr
Q	Two circular spots	Spacing: 2,5-7,5 mr Spot diameter: 10-15 mr Irradiance ratio: 1-9	Small spot diameter: 5 mr
R	Circular Top-hat ring with central spot	Spot diameter, ring diameter and Irradiance ratio	Ring thickness: 5 mr
S	Arbitrary shape	Size, shape, units, spacing, irradiance level	-
T	Apparent source of projector	Outer diameter: 3-96 mr	Circular aperture

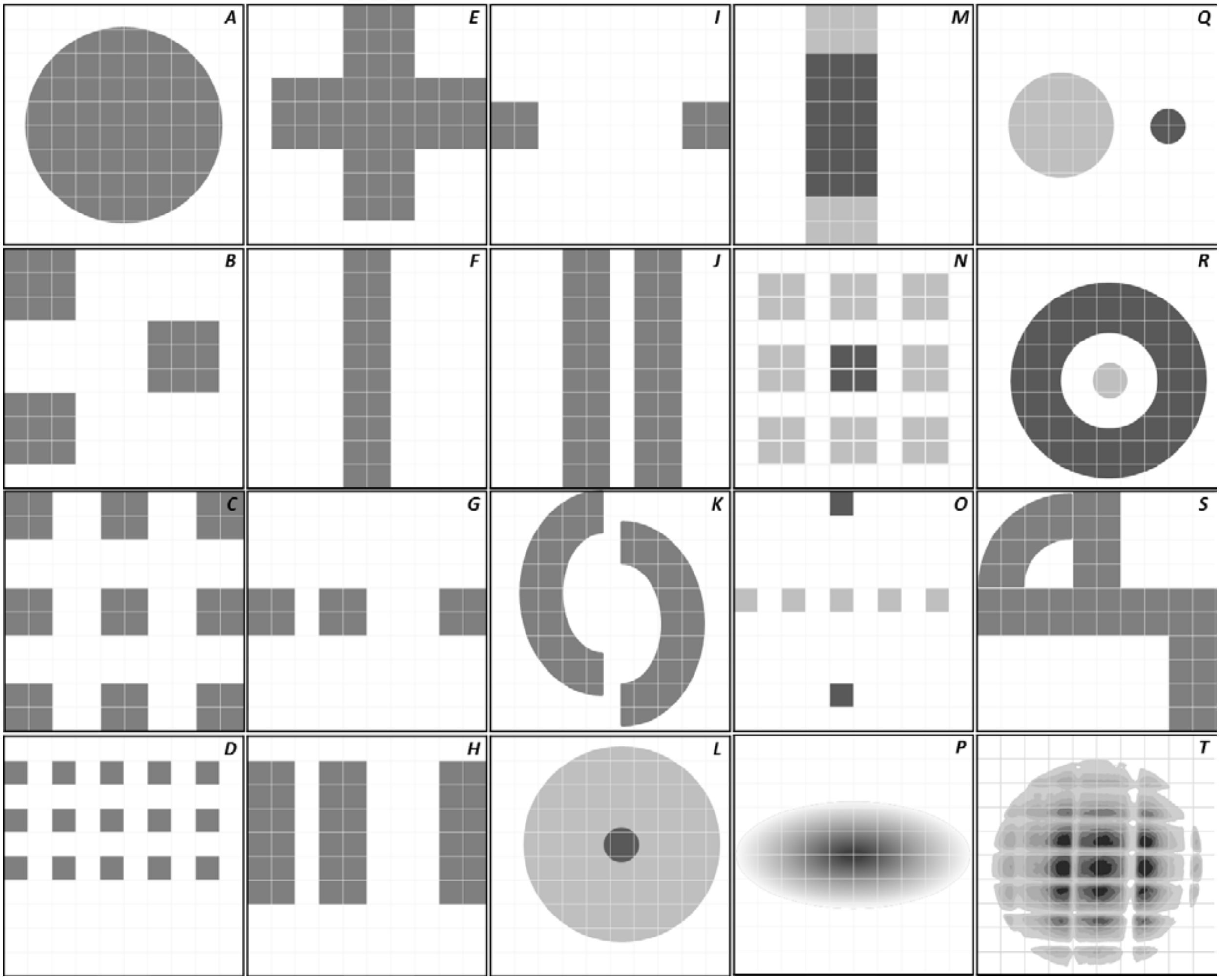

Figure 2. Illustration of the irradiance profiles (one characteristic example per series) investigated in this study; gray scale indicates varying irradiance levels

refers to the basic retinal thermal emission limit (i.e. $20000 \cdot t^{-0.25}$) multiplied by the solid angle subtended by a pupil of 7 mm in diameter and R(λ) is the retinal thermal weighting function. RF is the main figure used for evaluating the proposed method, which is considered as validated if, for all investigated irradiance profiles and exposure scenarios, the RF is neither too low (i.e. unsafe) nor more restrictive than the current method of IEC 62471. The lowest acceptable RF was set to 1.5. This level was determined by considering:

- the computer model deviation from to the experimental ED_{50} data. Among the available data (see [11]), a total of 68 ED_{50} were found for macular exposures and exposure durations shorter than 10 s, for which computer model predictions can underestimate the ED_{50} level by a factor of up to 1.29.
- that no RF obtained by applying the proposed method should be lower than the lowest RF obtained with the method currently applicable according to IEC 62471, namely 1.5 (see section "Results") obtained for a circular top-hat spot of 3 mrad in diameter and a 5 ms exposure at 530 nm.

During preliminary validation of the proposed method, the lowest reduction factor RF obtained by applying the proposed method without the factor 1.3 was 1.25. This safety margin was considered too small and it is therefore proposed to introduce the factor of 1.3 to increase the AE in the proposed analysis method. This adjustment ensures that the RF is in no instance lower than 1.5.

Results

Figure 3 shows the contour at 50% points according to as well as the applicable integration area resulting from the proposed method for a selection of image patterns. The size of the apparent source obtained with the proposed method is in most cases equal to or smaller than with the current restrictive method and the integration area is usually oblong in shape whenever a preferred orientation is apparent. In such cases, finding the critical rectangular integration area may require rotating the image to ensure that the global maximum was found. For instance, the highest ratio of AE to AEL found for image E of Figure 2 was obtained for a rectangular integration area rotated by 45°.

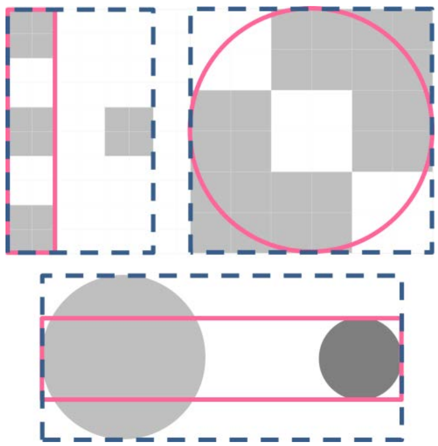

Figure 3. Illustration of 3 irradiance profiles superimposed with the source size at 50% points (dashed line) as well the source size according to the proposed method (solid line)

while the averaged THR (or AE in the case of product classification) will generally, depending on the distribution of radiance or irradiance, increase at a faster rate for smaller averaging areas. Consequently it often occurs that, the larger the image is, the larger the reduction of source size is and in turn the reduction of RF compared to the current applicable method.

As with the example of two square spots discussed in the section "Analysis method", the image analysis can often be performed analytically in the case of simple image patterns such as arrays or rectilinear polygons with or without hot spot, provided that the image can be decomposed in single elements of constant irradiance. As an example, it can be shown that the integration area of the optimized integration area of the left image in Figure 3 will always be the same regardless of the gap size, as long as the latter remains identical between all elements and that the image remains unconstrained by [αmin;αmax].

As the main figure of evaluation, the reduction factor RF is shown for all image patterns and exposure scenarios individually in Figure 4 where the results are ordered in series as in Table 1 and Figure 2. The RF obtained by applying the method currently applicable in IEC 62471 are shown for comparison. For all image patterns and exposure durations tested both at 530 nm and 1060 nm (32 paired samples), the RF was

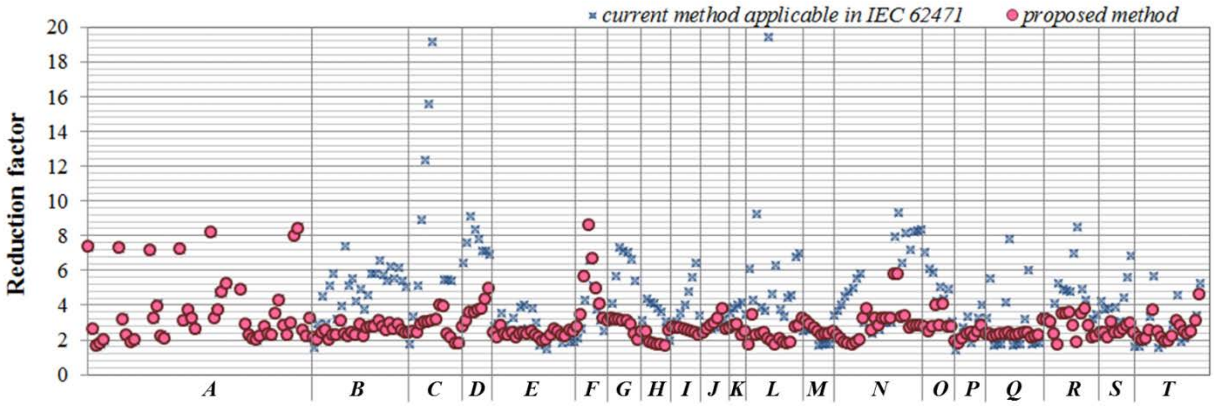

Figure 4. Individual reduction factor (ratio of computer model threshold to exposure limit) for the 292 exposures investigated in this study including pulsed exposures and 1060 nm; data are grouped into series ordered alphabetically (see section "validation")

In the examples of Figure 3, the RF was found to be 2.9, 2.4 and 2.4 (clockwise starting from top left), a value reduced by a factor of 1.7, 1.6 and 1.8 respectively as compared to the current restrictive method. This reduction is explained by the fact that the AEL increases in a linear fashion with decreasing α

consistently lowest for exposures at 530 nm, where the human eye is most sensitive to laser-induced lesions. By contrast, there is not a single exposure duration at which the RF consistently reaches a minimum because the result depends on the value of time-dependent αmax and the distribution of irradiance across the image. On overall, the RF was higher at 0.25 s than for shorter exposure durations (36 paired samples; $p<0.001$ for student's t-test) but in some instances it can drop by as much as 50% for very large spots compared to 0.25 s exposures. It is worthy to mention that the current restrictive method produces the highest

RF, or in other words most restrictive AEL, in the case of very large images where the contour at 50% encircles the entire image although the thermally-induced retinal injury is provoked by a much smaller part such as in arrays of spots distant from one another or in rings.

The overall distribution is described for both methods by the five-numbers summary in Table 2. By using the proposed method, the spread was significantly reduced without lowering the minimum value and 50% of the samples are concentrated at a level between 2.2 and 3.1 times higher than their respective EL.

Table 2. Descriptive statistic of the reduction factors (292 samples) obtained by means of two different methods

Parameter	Current restrictive method	Proposed method
Minimum	1.5	1.5
1st quartile	2.6	2.2
Median	3.6	2.5
3rd quartile	5.4	3.1
Maximum	22.6	8.5

Summary

A new method to determine the size of the apparent source for the purpose of classification according to IEC 62471 is proposed. The goal was to reduce the needlessly over-restrictive AELs without jeopardizing the safety margins implemented in the international standard for broadband radiation. This result was achieved by introducing an image analysis method that consists of identifying the partial area within the retinal image associated with the maximum ratio of accessible emission over AEL. Because the partial area over which the radiance is averaged is characterized by the parameter α and the AEL depends on the parameter α too, the result of this image analysis is a critical averaging area that eventually defines the quantity “angular subtense of the apparent source” as a parameter of the AEL.

The implementation of both circular and rectangular averaging areas for finding the source size is by all means necessary because some elongated profiles such as tubes cannot be safely evaluated with a circular aperture while axially symmetric profiles such as top-hat spots with a central hot spot are best evaluated with a circular aperture. Investigating only circular or rectangular averaging areas can lead to unsafe analysis, i.e. AEL level as high as injury threshold level (RF~1). This method is applicable to any irradiance profile regardless of its degree of complexity. In order to maintain a sufficient safety margin also for more critical retinal irradiance profiles, it was necessary to introduce a scaling factor of 1.3, thus increasing the accessible emission expressed as average radiance.

The current method will naturally remain generally applicable as a simplified conservative method, and in some cases, due to the scaling factor of 1.3 in the proposed method, the current method can actually be less restrictive than the proposed method, and therefore should remain applicable.

Finally, it must be noted that the approach for validating the method was empirical since a purely mathematical approach was not viable. As a result, it cannot be asserted that the most critical image pattern has been investigated (i.e. that the lowest reduction factor was found) and that the proposed method is unconditionally safe for any irradiance profile imaginable. However, in light of the diversity of profiles considered in this study, it is reasonable to say that the principle of averaging the radiance and maximizing the ratio of AE to AEL is appropriate for complex sources.

Acknowledgment

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Meet the Authors

Mathieu Jean received his Master’s degree in physical acoustics from the University Pierre & Marie Curie in Paris and is with the Seibersdorf Laboratories since 2007. He has developed physics-based models of thermally-induced damage to ocular tissues and skin, which he applies both to produce data to improve international exposure limits as well as for injury risk analysis of commercial products. Since 2008, he also works on his PhD at the Univ. Techn. Vienna on the modeling of laser induced injuries.

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.