KOMMENTARE ZUR ANWENDUNG VON ICNIRP LASER EXPOSITIONS-GRENZWERTEN

COMMENTS ON THE APPLICATION OF ICNIRP LASER EXPOSURE LIMITS

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Zusammenfassung *— ICNIRP Guidelines für Laserstrahlung enthalten Grenzwerte (exposure limits) und Messparameter wie Mittelungsblenden und Empfangswinkel. Details zu Analyseverfahren und zur Dosimetrie sind nicht im Umfang der ICNIRP Guidelines. Diese Information ist in anderen Schriften zu finden. Im vorliegenden Paper sollen diese Informationen zusammengefasst und spezifische Fragen zur Dosimetrie diskutiert werden, die bei Netzhautgrenzwerten relativ komplex sein können, vor allem seit der Aktualisierung der ICNIRP Guidelines im Jahr 2013. Beim photochemischen Netzhaut-Grenzwert sind konservativ angenommene Augenbewegungen die Grundlage für die Umrechnung von Strahldichte in Bestrahlungsstärke. Beim thermischen Netzhaut-Grenzwert ergeben sich bei ausgedehnten Quellen, die größer als der zeitabhängige Parameter "*α_{max}*" sind, Einschränkungen des Messwertes durch den Empfangswinkel. Für spezielle homogene Profile der scheinbaren Quelle kann dies alternativ durch einen Korrekturfaktor für* C_E *berücksichtigt werden; die Messungen werden dann mit einem „offenen" Empfangswinkel durchgeführt.*

Summary *— ICNIRP recommends exposure limits for laser radiation in the respective guidelines document. Also, measurement parameters such as the diameter of the limiting aperture and the angle of acceptance are specified. Detailed discussion of dosimetric (radiometric) principles and analysis methods are not in the scope of the ICNIRP Guidelines. Relevant information can be found in other documents. In this paper we review pertinent information and discuss specific issues that, for retinal limits for the 2013 revision of the ICNIRP guidelines, can be complex. For the retinal photochemical limit, conservative assumptions about eye movements are the basis for deriving the laser exposure limits from the basic radiance limit. For the retinal thermal limit, for the case of apparent source sizes exceeding the exposure-duration-dependent "*α_{max}*", the angle of acceptance reduces the measurement value; an alternative approach for homogenous source profiles is a correction factor for* C_E *and measurement with an open field of view.*

Schlüsselwörter *—ICNIRP, Laser, Dosimetrie, Netzhaut, Empfangswinkel*
Keywords *—ICNIRP, laser, dosimetry, retina, angle of acceptance*

1. Introduction

In 2013, ICNIRP published revisions of the laser [1] and the incoherent broadband [2] guidelines. Many of the exposure limits (EL) remained the same compared to earlier guidelines, but for pulsed, and particularly pulsed extended sources, EL were adjusted to more consistently reflect the dependence of the injury thresholds on retinal spot size and pulse duration. While dosimetric concepts were not changed, they became more important, for instance due to the decrease of α_{max} to 5 mrad for pulses shorter than 625 µs. The details of the changes of the EL will not be discussed in this paper (see references give in the ICNIRP guidelines); however, we would like to provide comments on issues that are sometimes the topic of critical comments, but can be resolved when considering dosimetric principles.

While the authors were involved in the development of the ICNIRP updates, it is important to point out that this paper is not in any way a comment by ICNIRP nor does it necessarily represent the view of the ICNIRP Main Commission.

2. Reduction Factor

There is the frequent notion, for many years, that the "safety margin" in laser exposure limits is generally 10, not only with respect to ICNIRP but also for ANSI Z136.1 [3] maximum permissible exposure values (which are almost identical to the ICNIRP exposure limits). The factor between the injury thresholds [4] for the non-human primate (NHP) to the EL has been designated as the "reduction factor" by ICNIRP. A significant misconception is that the reduction factor has been *generally* 10. As stated in the 2013 ICNIRP laser guideline, a minimum reduction factor of about 10 is desired for *point source EL*, i.e. for collimated laser beams entering the relaxed eye, producing a minimal retinal spot size. The reason why a minimum reduction factor of 10 is desirable, is the uncertainty associated to the thresholds, mainly due to uncertainties about the retinal spot size for humans, as is also noted in the ICNIRP guidelines. A review of experimental thresholds [5,6] shows that it cannot be excluded that the retinal spot size in the NHP experiment is equivalent to about 5 mrad, not 1.5 mrad (see also Figure 1 below). Explant and computer models predict [6,7] that the threshold for the case of spot sizes of 1.5 mrad is a factor of 3 lower as the threshold determined for the NHP. The deviation can be explained by assuming that the retinal spot size in the NHP experiment is 5 mrad and not 1.5 mrad. For the human exposure it cannot be excluded that the minimum spot size is as small as 1.5 mrad. When the reduction factor relative to the NHP experiment is 10, the actual reduction factor might be about 3 when an exposure results in a spot size of 1.5 mrad. This uncertainty about the injury threshold and the spot size is the background of the minimum reduction factor of 10 for small sources. To keep the minimum reduction factor at a level of about 10 for point source conditions was also the reason why, for single pulses in the nanosecond regime, the EL in the 2013 revision was lowered by a factor of 2.5, in further detail discussed at the end of this section.

For more recent NHP experiments with *extended sources*, there is little uncertainty associated with the injury thresholds (several different studies and data points are all consistent [8,9,10]), since the retinal spot size can be characterised well and also the determination if a lesion was induced is easier as compared to a point source with a nominal diameter of the beam at the retina of only 25 µm. Therefore, for the case of experiments designed to determine the threshold for extended sources, the ICNIRP 2013 guidelines note that a reduction factor of 2 is thought to be sufficient (see ICNIRP laser guidelines, section "Reduction factors" page 281).

Some comments on the 2013 ICNIRP guidelines see a "paradigm change", based on the "change from a reduction factor of generally 10 to generally 2 for the 2013 revision". These comments, however, miss two important issues:

1) For **point sources**, the minimum reduction desired in the ICNIRP EL is **still about 10** (as before!), which was the very reason why the nanosecond single pulse EL was reduced by a factor of 2.5 in the 2013 update.
2) For **extended sources, the reduction factor was about 2-3 already in the earlier ICNIRP guidelines**[1], for instance for 100 ms, shown in Figure 1.

It is apparent from studying available literature that the reduction factor was 2-3 for some cases already in earlier guidelines and that a reduction factor of 10 is still seen as necessary by ICNIRP for small sources, as long as the spot size uncertainty has not be resolved. The discussion of reduction factors in the 2013 ICNIRP laser guidelines gives the rationale as expressed above. In addition to the ICNIRP guideline text, the data offer pertinent "proof" (see below Figure 1 for 100 ms and threshold data for the nanosecond regime where the EL were lowered, discussed below). Hence, **it is not correct to assume that the 2013 revision represents a *"paradigm change, because the reduction factor was changed from 10 to 2"*.**

It is not in the scope of this paper to discuss reduction factors in detail, but an important aspect in the discussion of the reduction factor between thresholds determined with a NHP model and EL for humans is that the NHP retina is an "accurate" model for the human, where it is known that thresholds for the humans are not lower than for NHP [11,12,13]. That is, the NHP experimental model is more sensitive as compared to the human retina, even heavily pigmented human retinas. Thus there is no uncertainty when it comes to transfer thresholds from the NHP model to humans, in the sense that humans might be more sensitive; on the contrary, all available data show that the human is less sensitive, so that the reduction factor for humans is larger as for the NHP model.

Another important aspect in the discussion is that thermal injury is strongly non-linear with temperature [14,15]. As a consequence, the degree of thermal insult (which can be modelled well with the Arrhenius integral) depends strongly on the temperature. Even if the temperature is only slightly lower than the critical temperature, thermal injury potential is drastically reduced [15], i.e. there is no relevant risk for thermally induced injury. This is important when it comes to reduction factors. When it is known that the critical temperature increase (leading to a minimal injury) is for instance 20 °C for exposure durations of 2 seconds (see Fig. 2 in [2]), then exposure at half the threshold exposure value (reduction factor of 2) will lead to half the temperature increase, i.e. 10 °C. Based on the non-linearity of thermal injury it is known that such a temperature increase does not have any relevant thermal "action potential" for the respective exposure duration. A reduction factor of 10 would reduce the temperature rise to 2 °C degrees. Even a fever, which does not lead to retinal thermal injury when "exposed to" over days, produces a higher temperature increase. A factor of 10 reduction (1000 %) is not necessary for thresholds where the dosimetry has little uncertainty, where the animal model is known to be more sensitive, and where thermal injury is highly non-linear with temperature. The situation is different for retinal photochemical injury, where a reduction factor larger than 2 is needed due to higher uncertainties as compared to retinal thermal injury; for the assumed pupil diameter of 3 mm for the derivation of the basic radiance dose limit, the reduction factor compared to the threshold by Lund for 100 seconds exposure duration and a wavelength of 441 nm [16] is 23.

The reduction factor arguments are best supported by the data shown in Figure 1. This plot was, for instance, also shown and discussed in the plenary presentation by Karl Schulmeister

[1] The difference of the 2013 update to earlier guidelines is that needlessly large reduction factors for pulses and large sources were reduced; i.e. the updated EL follow the injury thresholds more consistently, with an appropriate reduction factor.

at NIR 2011 in Dortmund, but is also found in a review by Schulmeister, Stuck, Lund and Sliney 2011 [6].

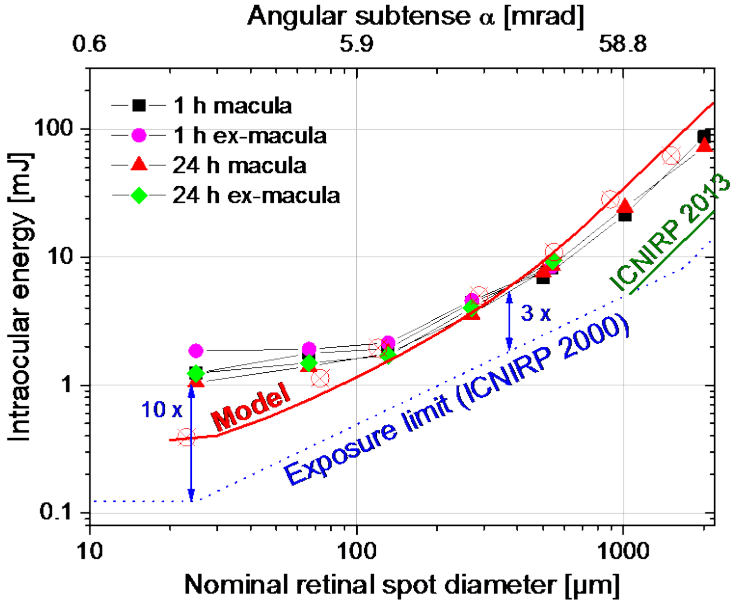

Fig. 1: Example of injury threshold studies for 100 ms pulse duration and wavelengths in the green range for varying retinal spot sizes. For 100 ms pulse duration, the EL did NOT change for spot sizes of up to 63 mrad (1.1 mm on the retina), which is the new α_{max} (α_{max} was 100 mrad before). Thus it is clear that for this case, the reduction factor between about 5 mrad and about 60 mrad was 2-3 for the earlier EL as well as for the 2013 revision. Also the issue of potentially smaller thresholds for small spots can be seen by comparison of the NHP thresholds with explant (symbol: crossed circle) and computer model data.

For the nanosecond regime, we point out that for the earlier (pre-2013) EL guidelines, the single pulse EL for visible radiation and small sources was 0.2 µJ when expressed as intra-ocular energy. Worst-case exposure parameters[2] [8] of 532 nm wavelength, 5 ns pulse duration, point source condition and exposure in the macula of a rhesus monkey with an endpoint of 24 hour observation of the lesion resulted in a threshold equal to 0.64 µJ. Compared to the earlier (pre-2013) EL the reduction factor is 3.2; this was apparently believed to be too small for a point source condition and consequently in the 2013 revision, the EL was reduced by a factor of 2.5, establishing a reduction factor of about 10. It is worth noting that laser bio-effects experts from the UK commented in the public consultation phase of the draft 2013 guidelines, that such a reduction does not appear to be warranted, i.e. from their perspective, the ICNIRP guidelines are too conservative.

3. Beam diameter definition not needed

Some health physicists have voiced the comment that it is necessary for ICNIRP to define the method to determine a "beam diameter" that is applicable also to complex irradiance profiles.

Such a request neglects that ***none of the EL depend on the beam diameter*** that is incident on the eye or the skin. While it is correct that for a given total power in the beam, the exposure

[2] Earlier experiments did not combine these worst-case conditions and resulted in higher thresholds.

level (irradiance profile) of course depends on the "size" of the beam, it has to be emphasised that the EL do not have the beam diameter as a factor.

It is well known that the *injury thresholds* of the skin and the cornea depend on the beam diameter, with larger beam diameters featuring lower injury thresholds [17,18], but the EL were set as a constant value, based on the worst-case thresholds, and do not feature a dependence on beam diameter. The only exception is the retinal thermal EL, which depends on the angular subtense of the apparent source α. However, α is not a beam diameter, α is an angular subtense, and it is not related to the beam diameter that is incident on the cornea of the eye (α is basically the angle subtended by the retinal irradiance profile as seen from the pupil of the eye). When the beam diameter at the eye is smaller than the pupil or when the radiation is completely incoherent, then the retinal image is related to the beam irradiance profile where the eye is accommodating to, but in other cases the retinal image is smaller, due to the effect of the pupil. The ICNIRP guidelines give a method ([1] page 288, Section "Thermal") of how to determine α for non-uniform retinal profiles by maximizing the ratio of the exposure within angle of acceptance γ to the EL determined for $\alpha = \gamma$.

The concept of exposure level analysis as followed by ICNIRP (not only since the last guidelines) is to define limiting apertures for the determination of the exposure level that is compared against the EL. The exposure level, expressed as average irradiance, is determined with these limiting apertures by determining the power that passes through the limiting aperture P_{ap} and dividing P_{ap} with the area of the limiting aperture. In this way, the irradiance (or radiant exposure as time-integrated irradiance) that is compared against the EL is averaged over the limiting apertures. This is the well-known radiometric concept since the definition of the first EL, not only by ICNIRP but also for instance by ANSI Z136. **For this process, however, it is NOT necessary to define some kind of "beam diameter".** The averaged exposure level is simply the power that passes through the aperture that is divided by the area of the aperture, irrespective of what the beam diameter is (and the EL neither depends on the beam diameter).

Sometimes a "beam diameter" is useful when the power P_{ap} is not measured but *calculated*. It is possible to accurately calculate P_{ap} for a well-defined profile such as a Gaussian irradiance profile being incident on the limiting aperture and some part of the beam being outside of the limiting aperture. When the total power in the beam is known, with a proper definition of "diameter" of that Gaussian profile, or a top-hat profile, it is possible to calculate the power P_{ap} that passes through the aperture with area $A_{aperture}$, and with that, the correctly averaged irradiance $E_{av} = P_{ap}/A_{aperture}$. For irregular profiles, the actual irradiance profile (a two - dimensional information) is needed to place a software aperture on the irradiance profile data and search for the location in the profile which results in the maximum value of P_{ap}. It is *NOT POSSIBLE* to come up with a beam diameter definition that generally results in the correct value of the average irradiance E_{av} when the *total* power is divided by the area defined by the "beam diameter". A one-dimensional quantity (a "beam diameter") can simply not represent the information of a two dimensional quantity (the irradiance profile) sufficiently to be useful for an accurate determination of P_{ap} and the respective average irradiance E_{av}. For all but specific cases of top-hat profiles or Gaussian profiles, where a beam diameter can be properly defined, the power either needs to be measured through the limiting aperture (with a diameter as defined by ICNIRP), or the irradiance profile is determined for instance with a CCD camera and then the analysis can be done with a software aperture. **The parameter "beam diameter" is, for the general concept as defined by ICNIRP, not needed and also cannot be properly defined for arbitrary irradiance profiles.**

We also would like to voice a word of caution: sometimes the 2nd moment beam diameter method is considered as a proper way to calculate the "beam diameter" for laser safety. The 2nd moment method is even described in an ISO standard series (ISO 11146 [19]). While the 2nd moment method is an interesting theoretical concept and has its merits, it also has serious drawbacks. The underlying problem is that the 2nd moment method weighs the irradiance profile with the square of the distance to the centre of the profile. This results in 2nd moment diameters, that are often "too large". For instance, the "diameter" of a ring profile (Figure 2), when determined with the 2nd moment method, is larger than the outer diameter of the ring! Further details can be found in a SPIE proceedings paper [20]. Clearly, when some sort of "average irradiance" or "power through aperture" is calculated by using a beam diameter that is too large, an erroneously low exposure value is the result, i.e. the analysis errs on the wrong side of safety.

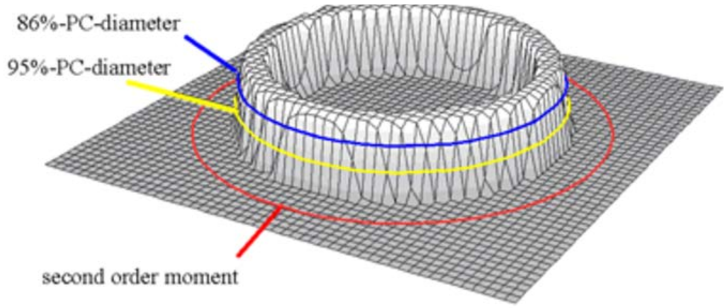

Figure 2. Irradiance profile of a ring mode; the second moment diameter is significantly larger than the outer diameter of the ring. Image courtesy of Bernd Eppich, Berlin.

4. Conservative eye movements as basis for photochemical retinal limit

4.1 Summary of derivation of laser limits

Some health physicists question if and how eye movements are considered in the retinal photochemical limits. We would like to provide information about the relationship between the basic radiance dose limit and how the laser safety limits were derived based on restrictively assumed extent of eye movements. The information provided in this section of the paper, however, can also be found in the CIE/ICNIRP "Measurement of Optical Radiation Hazards" book from 1998 [21] as well as in reference [22].

It is vital to acknowledge that the following two expressions A) and B) are two fully equivalent ways to express the same limit (expressed in two different radiometric quantities), provided that the angle of acceptance γ_{ph} is used appropriately (the symbols as used for the 2013 incoherent broadband guidelines were used here for the EL, the subscript "B" being derived from the "blue light hazard").

A) The retinal photochemical EL when expressed as "corneal" limits are (both for the 2000 and the 2013 laser guidelines):
For exposure durations between 10 s and 100 s: $H_B^{EL} = 100\ C_B\ J\ m^{-2}$
For exposure durations > 100 s: $E_B^{EL} = 1\ C_B\ W\ m^{-2}$

B) The EL can, alternatively, be expressed as radiance dose for exposure durations of 10 s to 10 000 s: $D_B^{EL} = C_B\ 10^6\ J\ m^{-2}\ sr^{-1}$
and for exposure durations > 10 000 s, as radiance of $L_B^{EL} = C_B\ 100\ W\ m^{-2}\ sr^{-1}$

The angle of acceptance γ_{ph} is the "link" between A) and B). The value of γ_{ph} depends (Table 1) on the exposure duration *t* and is derived, as discussed in the ICNIRP guidelines (both 2000 and 2013; the 2000 guidelines did not yet use the specific symbol γ_{ph}) from a conservatively assumed angular extent of eye movements. The plane angle γ_{ph} is related to the respective solid angle Ω_{ph} (no specific symbol was used in the ICNIRP guidelines) by

$$\Omega_{ph} = \frac{\gamma_{ph}^2 \cdot \pi}{4}$$

This is the solid angle subtended by a circle that subtends the plane angle γ_{ph}.

Table 1

10 *s* – 100 *s*	γ_{ph} = 11 *mrad*	$\Omega_{ph} = 10^{-4}$ *sr*
100 *s* – 10 000 *s*	$\gamma_{ph} = 1.1\sqrt{t}$	$\Omega_{ph} = 10^{-6} \cdot t$ *sr*
> 10 000 s	γ_{ph} = 110 *mrad*	$\Omega_{ph} = 10^{-2}$ *sr*

The relationship between A) and B) is simply that the limit expressed as corneal exposure (E, H) is equal to the radiance limits (L, D) multiplied with the defined solid angle Ω_{ph}:

$$H_B^{EL} = D_B^{EL} \cdot \Omega_{ph}$$

For instance, the limit of 100 J m^{-2} is derived from 10^6 J m^{-2} sr^{-1} by multiplication with the solid angle of $\Omega_{ph} = (0,011)^2\ \pi/4$. **Thus there is no question that the EL of 100 J m^{-2} defined for exposure durations between 10 s and 100 s incorporates eye movements of the extent of 11 mrad.** For exposure durations exceeding 100 s, the dependence of Ω_{ph} on *t* compensates for the dependence of the exposure dose (for a given exposure expressed as irradiance) on *t* ($H = E \cdot t$) and the limit can be expressed as a constant corneal irradiance to be compared against the time-weighted average corneal irradiance (note, however, that for apparent source profiles that are larger than $\gamma_{ph}(t)$, the measurement value increases within increasing *t*, as γ_{ph} increases with *t*, see following paragraphs).

The angle γ_{ph} is not only the basis for the transformation of the exposure limits in terms of units used to express the same limit, it is also the angle of acceptance for the determination of the exposure level that is to be compared against the EL (see Figure 3); by using the specified angle of acceptance γ_{ph} (in a way that is appropriate for the measurements), **the above two presentations A) and B) are identical, i.e. the ratios of exposure level over exposure limit are equal.**

It is interesting, as already noted in the 1998 CIE/ICNIRP Handbook [21, 22], that the angle of acceptance γ_{ph} has different functions for the two manifestations of the photochemical retinal limit A) and B): for the radiance limit, γ_{ph} is an *averaging* angle, expressing directly that eye movements lead to an averaging of the retinal irradiance (radiance is directly related to retinal irradiance); when the retinal image[3] is *smaller* than γ_{ph}, then the averaging effect reduces the measured radiance value; for retinal images <u>larger</u> than γ_{ph} and a homogeneous retinal irradiance profile, the angle of acceptance <u>has no effect</u> (in the same way as the 3.5 mm averaging aperture for the determination of skin exposure levels has no averaging effect

[3] We have intentionally used „retinal image" here and not the symbol α, which was sometimes used in ICNIRP guidelines as short-hand for "retinal image" or "apparent source". It is better to avoid the symbol α for the discussion of the photochemical limits, as for non-top hat retinal images (such as oblong images) the value of α does not represent the maximum dimension of the image, but the average of the two dimensions.

when the beam is larger than 3.5 mm and the irradiance profile is homogenous). Thus, for radiance (or radiance dose) measurements, γ_{ph} is an *averaging* angle of acceptance. On the other hand, for the expression of the limit as "corneal" limit, γ_{ph} is a limiting angle of acceptance in that it reduces the measured exposure value when the retinal image is *larger* than γ_{ph}, and has no effect on the measurement when the retinal image is smaller than γ_{ph}. For corneal irradiance (or radiant exposure) measurements, γ_{ph} is a *limiting* angle of acceptance, since it limits the measurement value to the part that is within the angle of acceptance γ_{ph}.

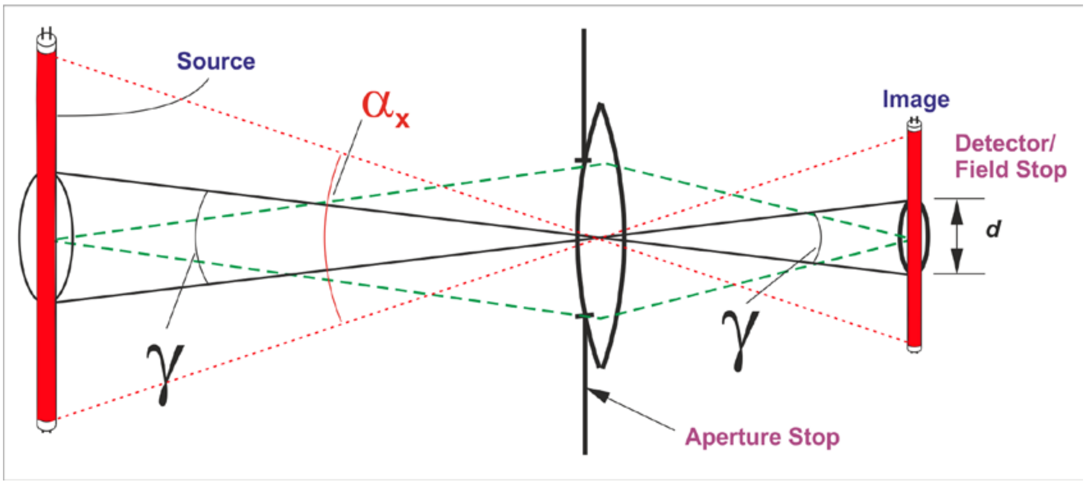

Figure 3: Set-up to achieve a well-defined angle of acceptance by placing a field stop in the image plane. The measurement field stop subtends a plane angle denoted by the symbol γ.

When considering the geometrical set-up of "corneal irradiance" measurements (Figure 3, corneal irradiance measured at the position of the aperture stop or limiting aperture) it becomes clear that the measurement[4] angle of acceptance γ, as a basic radiometric principle (which has nothing to do with photochemical limits) does not affect the measurement as long as the irradiance profile in the image plane (the retina) is smaller than the field stop that defines the angle of acceptance. This is also meant in the "restrictions" given in Table 5 of the 2013 laser guidelines (where version "A" of the limit is used) which read:

1) For $\alpha > \gamma_{ph}$
use $\gamma = \gamma_{ph}$ mrad
2) For $\alpha \leq \gamma_{ph}$, γ not
restricted

Instead of the symbol α it would have been more generally applicable if "retinal image" or "apparent source" had been used, but 1) means that when the retinal image is larger than γ_{ph}, then the measurement angle of acceptance γ should be limited to γ_{ph} (if not, the measured value is needlessly large) and 2) means that when the retinal image is smaller than γ_{ph}, then the specific value of the measurement angle of acceptance has no influence on the measurement and it can be "any" angle of acceptance, as long as it is larger than the retinal image. Such a set-up is also often referred to as "open field of view", i.e. a radiometer which does not have a specific field of view, as for instance a silicon detector without optics or without a Gershun tube [23]. This is also the advantage of expressing the photochemical retinal limit as corneal irradiance (what is referred to in the incoherent broadband limits as "small source limit"): as long as the retinal image (or "the apparent source") is smaller than

[4] We use the symbols chosen in the ICNIRP 2013 guidelines, where the symbol γ (without subscript) is used to indicate the measurement angle of acceptance which is defined by the field stop placed in the image plane.

γ_{ph} (in both dimensions), the actual size of the retinal image has no relevance for the measurement and neither has the angle of acceptance of the radiometer (as long as it is larger than the apparent source). There is no need to bother about the angle of acceptance of the radiometer and any kind of regular power meter can be used for the measurement (with the limiting aperture of 7 mm close to the sensor surface). In this way, the text in the 2013 ICNIRP guidelines in the section with recommendations on measurement is also consistent with the specifications given in Table 5 of the ICNIRP guidelines:

> **Photochemical**
> For comparison of the exposure from sources smaller than 11 mrad with the photochemical limits, expressed as irradiance, or radiant exposure, and for all exposure durations (10 s–30 ks), any acceptance angle larger than the source size can be used. For sources greater than 11 mrad

However, this text in the measurement section of the ICNIRP guidelines is not a „requirement“, rather it is based on a general concept of radiometry, and is equivalent with *“2) For $\alpha < \gamma_{ph}$, γ not restricted”* of Table 5. Based on radiometric principles, the above note in the ICNIRP guidelines, referring to apparent sources smaller than 11 mrad, can actually be generalized to apparent sources less than $\gamma_{ph}(t)$ for which case “any acceptance angle larger than the source size can be used”. This is the content of Note 2) in Table 5.

On the other hand, it is neither a “requirement” for a hazard analysis based on the corneal limits to apply a limiting angle of acceptance equal to γ_{ph} when the apparent source is larger than γ_{ph}. For simplicity and as a worst-case analysis, often an open field of view is chosen (such as a bare silicon or thermopile detector without optics or Gershun tube). When the exposure level determined that way is below the EL, then the measurement with a limited angle of acceptance will also be below the EL. Thus this simplified analysis method errs on the side of safety.

It is emphasized again that the photochemical retinal EL does not depend on the size of the retinal image[5] (only the thermal retinal EL depends on α via C_E). That the photochemical injury threshold (and EL) does not depend on the retinal irradiance profile diameter is based on biochemical and biophysical principles, since for any kind of photochemical interaction (such as exposing of photographic film, or skin exposure to UV radiation) it is just the local irradiance and exposure duration which is relevant, and there is no influence by other parts of the exposed tissue.

4.2 What the ICNIRP guidelines say

Additional to the presentation in the section above, in the following, we review the text of the guidelines.

The ELs for the retinal photochemical hazard were already given in the 2000 laser guidelines as follows:

[5] Therefore the parameter α_{min} also has no relevance for the photochemical retinal EL.

Page 435 ICNIRP 2000:

2. For the CW photochemical ("blue-light" or photoretinitis) EL, the Commission recommends a limit of 100 C_B J m^{-2} defined for a measurement cone-angle-of-acceptance (FOV, γ) of 11 mrad for $t \leq 100$ s. For $t >$ 100 s, an increasing FOV $\gamma = 1.1\sqrt{t}$ is applied. These limits lead to the result that for any small source subtending an angle less than 11 mrad, this

radiance limit corresponds to a corneal irradiance of 1.0 C_B W m^{-2} (0.1 C_B mW cm^{-2}) for $t > 100$ s. This

Table 3 of ICNIRP 2000:

400–600 nm	1 s < t < 100 s	H = 10 C_B mJ/cm^2 where FOV γ = 11 mrad, (i.e., Ω = 10^{-4} sr), and equivalent to: L = 100 C_B J/(cm^2 sr) where FOV γ = 11 mrad.	Photochemical: Assumes FOV γ = 11 mrad which is over-conservative for t > 100 s; therefore, a new proposal for meas. FOV $\gamma = 1.1\sqrt{t}$ mrad for t > 100 s (Ω = t μsr)
	100 s < t < 10^4 s	E = 0.1 C_B mW/cm^2 (i.e., L = 100 C_B J/(cm^2 sr) for meas. FOV $\gamma = 1.1\sqrt{t}$ (mrad, important when α > 11 mrad).	First dual limit to protect against photochemical injury (i.e., photoretinitis).

We note that already the ICNIRP 2000 guidelines defined the measurement angle of acceptance (or "field of view" FOV) to be 11 mrad for exposure durations up to 100 s and equal to 1.1 √t for exposure durations above 100 s. However, the ICNIRP 2000 guidelines, the specific symbol γ_{ph} has not yet been developed for the specification of the "restriction" on the measurement angle of acceptance.

Identical ELs are given in the 2013 laser guidelines, but are presented somewhat differently (for instance, m^2 was used instead of cm^2; in Table 5 of the guidelines, "version A" of the limits is presented):

Photochemical[c]				
$400 \leq \lambda < 600$	10 s	100 s	100 C_B J m^{-2}	1) For $\alpha > \gamma_{ph}$ use $\gamma = \gamma_{ph}$ mrad
$400 \leq \lambda < 600$	100 s	30 ks	1.0 C_B W m^{-2}	2) For $\alpha \leq \gamma_{ph}$, γ not restricted

And in Table 6 of the 2013 laser guidelines the limits are expressed as radiance dose and radiance, i.e. version "B)" of the limits:

Photochemical				Photochemical radiance EL valid for all α, but averaging of exposure level over γ_{ph}
$400 \leq \lambda < 600$	10 s	10 ks	1.0 C_B MJ m^{-2} sr^{-1}	
$400 \leq \lambda < 600$	10 ks	30 ks	100 C_B W m^{-2} sr^{-1}	

It is a challenge for ICNIRP to present all the information in a short version in the tables, and it would have been more generally applicable if "angular subtense of apparent source" had been used instead of the symbol α. Section "Photochemical" in the 2013 laser guidelines, on page 288, provides additional information on the practical application of the averaging angle of acceptance:

Photochemical

For comparison of the exposure from sources smaller than 11 mrad with the photochemical limits, expressed as irradiance, or radiant exposure, and for all exposure durations (10 s–30 ks), any acceptance angle larger than the source size can be used. For sources greater than 11 mrad and exposure durations between 10 and 100 s, use an acceptance angle (γ) that is equal to γ_{ph} = 11 mrad. For exposure durations between 100 s and 10 ks, the angle of acceptance, γ, steadily increases with time and it defines the cone angle over which the irradiance is collected (Schulmeister 2001). Specifically, for exposure durations between 100 s and 10 ks and source sizes $\alpha > \gamma_{ph}$, an acceptance angle of $\gamma_{ph} = 1.1 \times t^{0.5}$ mrad should be used for comparison with the exposure limit expressed in irradiance (or radiant exposure). For sources greater than 110 mrad and exposure durations from 10 ks to 30 ks, the measurement acceptance angle for limits expressed in irradiance should be 110 mrad. A linear cone angle of 11 mrad is approximately equivalent to a solid angle of 10^{-4} sr and a linear cone angle of 110 mrad corresponds to a solid angle of approximately 10^{-2} sr.

4.3 Comment on level of conservativeness

Considering that 11 mrad is about the angular subtense of the thumbnail of an extended arm, and that 110 mrad is about the angular subtense of the fist of an extended arm (see Figure 4), we point out that the extent of the eye movements as reflected by the angle of acceptance γ_{ph} and contained in the laser limits is very small: they assume (for the respective exposure duration) that a person can stare at a bright source for 100 seconds and does not look anywhere outside of a range of the extent of the thumbnail as seen on an extended arm. The authors of this paper would see this as very difficult to achieve to the degree where it could be considered as not reasonably foreseeable (what is reasonably foreseeable is to maybe stare into a source with little eye movements for 10 seconds or a little longer, but not for 100 seconds).

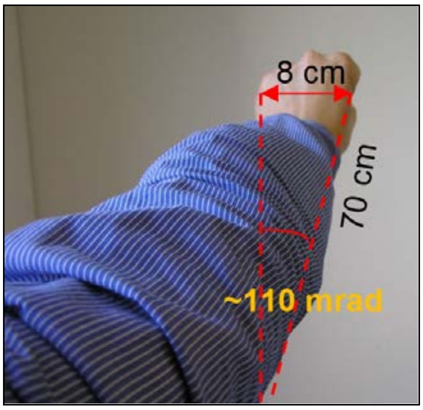

Figure 4. The angle subtended by the fist on an extended arm is approximately equal to 110 mrad, the very conservatively assumed extent of eye movements for an exposure duration of 2.7 hours.

Even more extreme is the assumption that the eye movements for 10 000 seconds exposure duration (2.7 hours) only cover the extent of the fist. Even if the person is on a chin-rest or the head is fixated, the gaze, for an exposure duration of 10 000 seconds will wonder over a field of view larger than just the fist on an extended arm. We see that the averaging angle of acceptance as recommended by ICNIRP is extremely conservative for all but very extreme (and not reasonably foreseeable) exposure scenaria.

For a more realistic exposure analysis, where eye movements are characterized or assumed for a specific scenario (such as a performer on a stage, being lit by spot lights) the 2013 ICNIRP incoherent broadband guideline mentions that specific eye movements can be considered ([2] page 90) and the underlying exposure limit is provided as retinal radiant exposure for that purpose. Such a more realistic analysis is, for instance, also reflected in the Austrian guide for workplace-safety assessment [24].

4.4 Summary on issues of eye movements for the photochemical retinal limit

The question, if eye movements are accounted for in the EL for laser radiation, is answered by pointing out that the EL are directly obtained from the base limit of 10^6 J m^{-2} sr^{-1} (see both ICNIRP broadband as well as ICNIRP laser limits) by multiplication with the solid angle subtended by the assumed eye movements. The eye movement extent is assumed in a extremely conservative way for exposure durations of up to 100 seconds of 11 mrad (equivalent to fixating only at the thumbnail of the extended arm) and for 10 000 seconds (almost 3 hours) of 110 mrad, equivalent to (Figure 4) fixation of the fist of the extended arm (and not looking anywhere else for almost 3 hours). The ICNIRP laser guidelines refer to this as “probably unreasonable” and we agree.

For an actual exposure analysis when using the laser EL expressed as corneal irradiance (or corneal radiant exposure), for the case that the retinal image is larger than the defined angle of acceptance, it is important to limit the angle of acceptance of the radiometer to the defined angle γ_{ph}, as otherwise the exposure value is needlessly high. Of course it is possible to perform a worst-case simplified analysis with an open field of view intentionally, in order to simplify the measurement.

We would like to point out that the discussion in this section does not provide any new information compared to earlier publications by ICNIRP and others. These other publications are also referenced by the ICNIRP 2013 laser guidelines.

5. Analysis of retinal images larger than α_{max}

5.1 Executive summary

Frequent comments relate to the parameter α_{max} and specifications of the angle of acceptance for the determination of the exposure level to be compared against the retinal thermal EL. The concept of α_{max} existed already in earlier ICNIRP guidelines (where α_{max} was a constant value of 100 mrad), but became more prominent in the 2013 update because α_{max} became exposure-duration dependent; as small as 5 mrad for exposure durations less than 625 µs.

For retinal images (apparent source profiles) exceeding α_{max}, the generally applicable assessment method is to limit the correction factor[6] of the retinal thermal limits, C_E to α_{max} /α_{min}, but at the same time to limit the angle of acceptance for the determination of the exposure level to a value equal to α_{max} (so that the exposure level that is compared against the EL is only a fraction of the power that passes through the 7 mm limiting aperture). This general method is also, for instance, adopted in the international laser safety standard IEC 60825-1. From this generally applicable method, for the special case of *homogenous circular* retinal image profiles ("top-hat" profiles), as an alternative method, the effect of the reduction of the exposure limit due to the limitation of the acceptance angle can be accounted for by an increase of the correction factor C_E beyond α_{max} / α_{min} with α^2. The exposure level is, for this alternative approach, determined with an "open" field of view (i.e. the acceptance angle is not relevant but has to be at least as large as the angular subtense of the apparent source). This could be called the "open FOV" alternative method. It is important to recognize that the open FOV method can be derived with simple radiometric principles and, for homogeneous retinal irradiance profiles, is mathematically identical to the general method in terms of hazard assessment (i.e. in terms of ratio of EL to exposure level that is compared against the EL).

While sometimes both methods are shown in one figure (for instance Figure A.8 of AKNIR Statement [25]) we recommend to keep the general method apart from the open FOV method. The misunderstanding could otherwise, for instance, be, that the method specified in IEC 60825-1 deviates from the ICNIRP guidelines, while in reality they are identical (the only difference is that the IEC standard does not provide the alternative "open FOV" method for the special case of circular homogeneous profiles, as the ICNIRP guidelines do).

The effect of the exposure-duration-dependent α_{max} was also, for instance, discussed in the NIR 2011 Dortmund paper [26] where the "open FOV" was emphasized when the retinal thermal limits were presented with a α^2 dependence for retinal images larger α_{max}. The background of the α^2 formula for top-hat profiles, which is given in the ANSI Z136.1 standard since 1993, and additional formulas for other profiles is discussed in the ILSC March 2017 proceeding by Marshall [27].

5.2 What the ICNIRP guidelines say

On page 276 of the 2013 ICNIRP laser guidelines [1], a special section is entitled "Large sources"[7]:

> **Large sources**
> Sources, that at the position of determination subtend an angle α larger than α_{max}, are referred to as large sources. For large sources, retinal injury thresholds when expressed as retinal radiant exposure are essentially independent of

[6] That is, it is the value of C_E that is limited by α_{max}, not the value of α generally; the retinal image can be larger than α_{max}.

[7] This term, strictly speaking, implies that the irradiance profile of the retinal image is circular; for oblong images it is possible that only one dimension is larger than α_{max} and therefore "large" while the value of α, as an average of the two dimensions, is less than α_{max}. For the limiting method, α is limited to α_{max} for each dimension before the average is taken, see example of line laser below.

spot size. The correction factor C_E becomes equal to $\alpha_{max}/\alpha_{min}$ when the field of view of $\gamma = \alpha_{max}$ is used to determine the exposure level. For a homogeneous and circular source, the exposure level can be determined with an open field of view and then the correction factor, C_E, is as defined in eqn (5):

$$C_E = \frac{\alpha^2}{\alpha_{min} \times \alpha_{max}} \qquad (5)$$

In the point of the view of the authors of this paper, the text and definitions of the guidelines cover both assessment methods sufficiently, while we acknowledge that they are not discussed in a very elaborate way. We would like to provide some additional comments in the following.

5.3 "Walk-through" comments

First of all it has to be appreciated that the section "Large sources" in the ICNIRP guidelines applies to apparent sources (retinal irradiance profiles) that are larger than α_{max}. The parameter α_{max} is defined elsewhere in the guidelines to be 5 mrad for exposure durations less than 625 µs and increases with the square-root of *t* up to 100 mrad for 0.25 s and longer exposure durations. The biophysical background is in detail discussed by Schulmeister, Stuck, Lund and Sliney [6]. In short, for irradiance profiles larger than $\alpha_{max}(t)$, radial cooling effects do not reach the center of the image within the exposure duration *t*. Therefore, the injury threshold, expressed as retinal irradiance or as radiance, no longer depends on the diameter of the image (the temperature in the center of the image is the same, independently of the image diameter). For a discussion on the relationship of retinal irradiance and radiance, see for instance [28,29,30].

In the following, first the method to limit C_E and the angle of acceptance is given, which we, in this paper, refer to as the "limiting method" in order to distinguish from the alternative "open FOV" method. It is emphasized that the "limiting method" is the generally applicable one, while the "open FOV" is an alternative method to perform the hazard analysis for large sources, but subject to special conditions.

For the limiting method, the correction factor C_E is limited to $C_E = \alpha_{max}/\alpha_{min}$ for the case that the angular subtense of the apparent source α is larger than α_{max}. For the case that the angular subtense of the apparent source α is smaller than α_{max}, the correction factor equals $C_E = \alpha/\alpha_{min}$, which is treated in the ICNIRP guidelines in the section "Intermediate sources". The limitation of the correction factor C_E to $\alpha_{max}/\alpha_{min}$ does not mean that retinal image of the apparent source cannot subtend an angle larger than α_{max}. This conclusion can, however, also be drawn from the first sentence of the guideline text reproduce above, as well as from several other sections in the guidelines, such as the section on "Intermediate sources":

> of retinal spot size. If the retinal image diameter becomes larger than a critical value, α_{max}, the radial heat flow does not affect the damage threshold when it is given as retinal radiant exposure (Schulmeister et al. 2008a, 2011). Since

For the “limiting” (general) method it is vital to recognize that the measurement angle of acceptance γ for the determination of the exposure level is also limited to the value of $\gamma_{th} = \alpha_{max}$. This is discussed in the following on the basis of the example of a top-hat profile as the apparent source (such as a diffuse disk), i.e. an apparent source that produces a circular retinal image with a constant retinal irradiance value (see Figure 5).

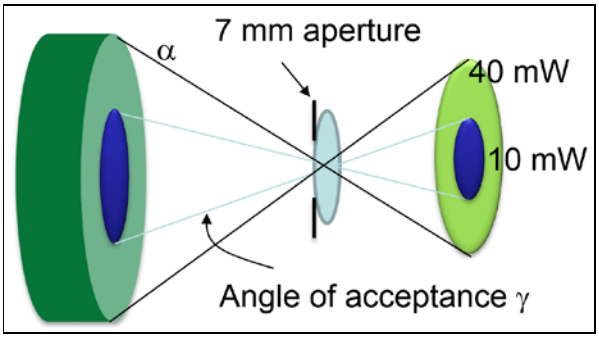

Figure 5. Example of an apparent source producing a „top-hat“ retinal image irradiance profile, which lends itself to the alternative method of accounting for the effect of the limiting angle of acceptance by a factor that increases the EL; the exposure level is then determined as „power through the aperture“, i.e. with an open FOV.

Let us assume that the angular subtense of this apparent source and of the retinal image equals $\alpha = 30$ mrad. Let us further assume that α_{max} equals 15 mrad (applicable for an exposure duration of 6 ms). This means that for the limiting method, the value of C_E is limited to C_E = 15/1.5 mrad = 10, but also the measurement angle of acceptance is limited to 15 mrad. If the power that passes through the 7 mm aperture is for instance 40 mW, then it is only the partial power that lies within 15 mrad that is considered to be the exposure level[8] (the value that is compared against the EL). Since the top-hat profile features a constant irradiance and is circular, that partial power within α_{max} is simply obtained to be equal to 10 mW: the total power entering the eye (or the measurement system through the 7 mm aperture) is 40 mW; this power is distributed evenly across the area of the image; the area of the image is 4 times as large as the area defined by the angle of acceptance (because the diameters feature a ratio of 2, the areas feature a factor of 4). Thus, for the limiting method, the EL with $C_E = 10$ (the actual value of the EL in Watt or Joules is not relevant here, only the value of C_E is) is compared against the exposure level equal to 10 mW (a factor of 4 lower than the power determined with an open FOV).

As a more general relationship, the factor κ is defined as the factor that the power within the angle of acceptance limited by α_{max} is smaller than the total power in the image (the power passing through the 7 mm aperture). ***For the example of a top-hat profile*, the factor is $\kappa = \alpha^2 / \alpha_{max}^2$ -** the ratio of the area of the image over the area that is defined by α_{max}.

Often it is easier to measure with an open FOV, by simply positioning the sensor of the radiometer closely behind the 7 mm limiting aperture (close enough so that the field of view is larger than the apparent source); for the above example the measured value would be 40 mW. When this “open FOV” exposure level were to be compared against the retinal thermal EL determined with the factor C_E limited to $\alpha_{max}/ \alpha_{min}$, the analysis would be highly

[8] The alternative representation of the retinal EL as „power through aperture“ is used here, as it is more intuitive, as compared to averaging irradiance over a 7 mm limiting aperture.

over-restrictive (but still possible, as a worst case simplified analysis). For the “open FOV” method, the factor κ that reduces the exposure level in the limiting method is used to increase the exposure limit beyond the value that it has in the limiting method (in the following, the symbol C_E is complemented with the respective superscripts to aid the “mathematical” presentation of the relationship of the two):

$$C_E^{open} = \kappa \cdot C_E^{\lim} = \kappa \cdot \frac{\alpha_{max}}{\alpha_{min}}$$ as a general relationship; and for the special case of a top-hat profile:

$$C_E^{open} = \kappa \cdot C_E^{\lim} = \kappa \cdot \frac{\alpha_{max}}{\alpha_{min}} = \frac{\alpha^2}{\alpha_{max}^2} \cdot \frac{\alpha_{max}}{\alpha_{min}} = \frac{\alpha^2}{\alpha_{max}\,\alpha_{min}}$$

which for the example above equals 40.

The EL obtained with $C_E^{open} = 40$ is then compared against the “open” exposure level of 40 mW.

We see that the ratio of exposure level to the exposure limit is in both cases identical: for the general “limiting” method, the ratio is equal to 10 mW/10 (i.e. both the EL as well as the exposure level is limited by α_{max}) while in the “open FOV” method, the ratio equals 40 mW/40 (i.e. neither the EL nor the exposure level are limited to α_{max}). *As long as the ratio between the exposure level and the EL are the same, the hazard analysis (the comparison of the exposure level with the EL) is identical.* It has to be emphasized that the alternative method with the open field of view is accurately reflecting the general limiting method ***only*** when the source is circular and homogeneous; but that is also clearly stated in the ICNIRP guideline text reproduced above.

In the same way the formula for the open FOV case was derived here with simple radiometric principles for a top-hat profile, it can also be derived for other retinal irradiance profiles, as long as the ratio (κ) of the total power entering the eye (or the radiometer) over the partial power within α_{max} is defined. Because the “open FOV” alternative can be simply derived on radiometric principles and is only applicable to constant irradiance profiles (which in practice are rare), in the IEC 60825-1 laser product safety standard, only the general “limiting” method is given. The lack of the “open FOV” method in the laser safety standard does not mean that the IEC standard is not consistent with the ICNIRP guidelines.

The concept is also not new to the 2013 ICNIRP revision (reflected in the 2014 revision of IEC 60825-1). The open FOV method has been already given in the 2000 ICNIRP laser guidelines. The general “limiting” method, for α_{max} = 100 mrad as constant value, was also found in IEC 60825-1:2007 (although up to now, as far as we know, no specific term has been used for the methods). Also the ANSI laser safety standard ANSI Z136.1 has, already in the 1993 edition, stated both the open FOV as well as the method with the limited C_E and the limited angle of acceptance (because ANSI is based mostly on calculations for workplace safety, the “open FOV” is more prominent there; IEC 60825-1 has always emphasized measurements over calculations, since the typical user is a testing laboratory for product safety). A word of caution, not to mix the two methods (as well as background information) can also be found in the Handbook by Henderson & Schulmeister 2004 [28] as well as in tutorials on laser safety calculations [30].

The "limiting method" is the general method, because it is also applicable for irregular (inhomogeneous) profiles, in which case the field of view defined by α_{max} is to be moved across the profile to determine the worst case position (to find the "hotspot"). Also FOV smaller than α_{max} are to be used in this "image" analysis, as described in the 2013 laser guidelines (page 288):

> **Thermal**
>
> For comparison of the exposure of uniform intermediate sources with photothermal limits in terms of irradiance, the acceptance angle γ must be at least as large as α.
>
> If the source is non-uniform, i.e., contains hot spots, an acceptance angle must be chosen so that it is sufficiently small to assess the hot spot but not less than 1.5 mrad nor greater than α_{max}. For each hot spot, or a non-uniform part of the source, assessed by an angle of acceptance, γ, the exposure must be compared with the limit applicable to a source size subtending an angle of α that is set equal to γ. The size and position of the angle of acceptance γ within the apparent source has to be adjusted to produce the most restrictive analysis (i.e., to maximize the ratio of energy determined within γ over α).

5.4 Alternative derivation of C_E^{open} for circular profiles

Above, the formula for the open FOV for the case of top-hat profiles was derived, based on the effect of the angle of acceptance on the exposure level. The same formula can be derived when it is considered that for the condition of $\alpha > \alpha_{max}$ the exposure limit, when expressed in terms of radiant exposure at the retina, is a constant (for large sources, the injury threshold and the EL – when expressed as retinal radiant exposure – does not depend on the diameter of the retinal image; see references Schulmeister et al. [6,31] for a discussion of the biophysical background).

We begin with the EL expressed as corneal radiant exposure, i.e. the "normal" EL, which can be written as the product of the point source EL, $H_{corn}^{EL\_point}$ (the value without the correction factor C_E) and the correction factor C_E; for circular retinal images up to α_{max} there is no difference between the "open" or the "limiting" method.

$$H_{corn}^{EL} = H_{corn}^{EL\_point} \cdot C_E$$

For $\alpha \leq \alpha_{max}$ $C_E = \alpha/\alpha_{min}$. For $\alpha = \alpha_{max}$, $C_E = \alpha_{max}/\alpha_{min}$.

The exposure limit expressed as retinal radiant exposure is obtained by multiplication of the corneal limit with the area of the pupil, A_{pupil}, as a first step, to obtain the limit expressed as "energy through pupil". As a second step, the retinal limit is obtained by dividing the "energy through the pupil" by the area of the retinal image (we neglect the transmission loss between the cornea and the retina, i.e. here the limit expressed as "retinal radiant exposure" H_{ret}^{EL} is based on measurements of power or energy outside of the eye, which is a common concept):

$$H_{ret}^{EL} = \frac{H_{corn}^{EL} \cdot A_{pupil}}{A_{image}} = \frac{H_{corn}^{EL\_point} \cdot C_E \cdot A_{pupil}}{A_{image}}$$

We then note that the area of the retinal image can be derived from the angular subtense of the image α and the distance of the retina to the principle plane of the eye *f*. For a retinal image that subtends an angular subtense **α equal to α_{max}**:

$$H_{ret\_\alpha\max}^{EL} = \frac{H_{corn}^{EL\_point} \cdot C_E \cdot A_{pupil}}{\pi/4 \cdot (f \cdot \alpha_{\max})^2}$$

We then express C_E as $\alpha_{max}/\ \alpha_{min}$:

$$H_{ret\_\alpha=\alpha\max}^{EL} = \frac{H_{corn}^{EL\_point} \cdot C_E \cdot A_{pupil}}{\pi/4 \cdot (f \cdot \alpha_{\max})^2} = \frac{H_{corn}^{EL\_point} \cdot \alpha_{\max} \cdot A_{pupil}}{\pi/4 \cdot (f \cdot \alpha_{\max})^2 \cdot \alpha_{\min}} = \frac{H_{corn}^{EL\_point} \cdot A_{pupil}}{\pi/4 \cdot f^2 \cdot \alpha_{\max} \cdot \alpha_{\min}}$$

As a second step, we express the EL as retinal radiant exposure for the case of **α > α_{max}** (for the open FOV approach, α is not limited to α_{max}). As a basic radiometric principle, retinal radiant exposure is obtained by dividing the "energy through the aperture" by the "area of the image". The area of the image is given by $(\pi/4)\ f^2\ \alpha^2$. The "energy through aperture" is based, as above, on the EL expressed as corneal radiant exposure multiplied with the area of the pupil (but alternatively, the EL expressed already in terms of "power through the aperture" can be used). The EL for this regime of $\alpha > \alpha_{max}$ is the point source limit times some – so far unknown – factor C_E^{open}. Note that the analysis is based on the total power that enters the eye, not just the part that is within α_{max}, and therefore the factor is C_E^{open}.

$$H_{ret\_\alpha>\alpha\max}^{EL} = \frac{H_{corn}^{EL\_point} \cdot C_E^{open} \cdot A_{pupil}}{\pi/4 \cdot (f \cdot \alpha)^2} = \frac{H_{corn}^{EL\_point} \cdot C_E^{open} \cdot A_{pupil}}{\pi/4 \cdot f^2 \cdot \alpha^2}$$

We then obtain C_E^{open} by equating the retinal EL for $\alpha = \alpha_{max}$ with the retinal EL for $\alpha > \alpha_{max}$, because we know that for large images (i.e. $\alpha > \alpha_{max}$), the EL expressed as retinal exposure is independent of the image size. Therefore, the retinal EL for $\alpha > \alpha_{max}$ has to be equal to the retinal EL for $\alpha = \alpha_{max}$:

$$\frac{H_{corn}^{EL\_point} \cdot A_{pupil}}{\pi/4 \cdot f^2 \cdot \alpha_{\max} \cdot \alpha_{\min}} = \frac{H_{corn}^{EL\_point} \cdot C_E^{open} \cdot A_{pupil}}{\pi/4 \cdot f^2 \cdot \alpha^2},$$

and we see that:

$$C_E^{open} = \frac{\alpha^2}{\alpha_{\max} \cdot \alpha_{\min}}$$

5.5 Cases other than a circular profile

The "open FOV" method also lends itself to be applied for retinal irradiance profiles other than circular ones, particularly if the irradiance profile is constant. As an example (for general formulas, see [27]), let us assume accommodation to infinity and exposure to a line laser. In this case, the retinal image is a thin line, with minimal "thickness" of 1.5 mrad and a "length" given as 70 mrad for the case of a 7 mm pupil located at 10 cm from the line shaping optics (Figure 6).

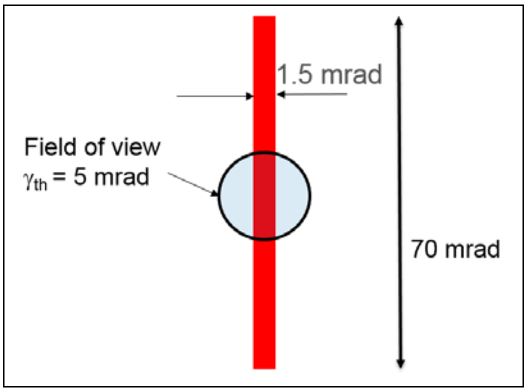

Figure 6: Retinal image resulting from a line laser for accommodation to infinity; the exposure level for the "limiting" assessment method is the partial power that passes through the circular field of view, in this example 5 mrad; not drawn to scale.

Let us further assume the exposure duration (pulse duration) is shorter than 625 µs, so that α_{max} = 5 mrad. The thin dimension (x) of the line is smaller than α_{max} and there is no limitation on α_x by α_{max}. The long dimension (y) is longer than α_{max}, so for the general method (the "limiting" method), α_x is limited to 5 mrad. Since α, for non-circular sources is determined as the average, the value of α for the limiting (general) method equals:

$$\alpha_{\lim} = \frac{\alpha_x + \alpha_y}{2} = \frac{\alpha_{\min} + \alpha_{\max}}{2} = \frac{1.5+5}{2} = 3.25 \ ,$$

and using the symbol $\alpha_{\lim}$ to indicate that α is limited to α_{max} here (in each dimension separately)

$$C_E^{\lim} = \frac{\alpha_{\lim}}{\alpha_{\min}} = \frac{\frac{\alpha_{\min} + \alpha_{\max}}{2}}{\alpha_{\min}} = \frac{3.25}{1.5} = 2.17$$

At the same time, when the power entering the eye (or the radiometer with a 7 mm limiting aperture) equals, for instance, 14 mW, then the exposure level is equal to the partial power that falls within an angle of acceptance of 5 mrad. For the line-laser example the power reduction is simply the ratio of the length of the line to the angle of acceptance, i.e. κ = 70 mrad / 5 mrad = 14. Thus the exposure level to be compared with the general (limited) C_E equals 14 mW / κ = 1 mW.

For the open FOV method, the full power that passes through the aperture is used as exposure level, i.e. 14 mW, but the exposure limit is determined with the larger, "open" C_E, which is, equivalent to the above derivation for a top-hat profile:

$$C_E^{open} = \kappa \cdot C_E^{\lim} = \frac{\alpha_y}{\alpha_{\max}} \cdot C_E^{\lim} = 14 \cdot 2.17$$

The respective larger EL is compared against the full power that passes through the 7 mm aperture.

Again the ratio of exposure level to EL is the same for the "limiting" and the "open FOV" assessment.

5.6 Presentations have to be consistent

In IEC 60825-1, only the generally applicable "limiting" method (limiting C_E to α_{max} /α_{min} and using α_{max} to limit the angle of acceptance) is given; the method derived for the special cases of a top hat profile, with the α^2-formulation (C_E^{open}) and an open measurement FOV, is not given in IEC 60825-1. However, we emphasize again that the α^2 formula can be derived by simple radiometric principles and is not, as such, a special requirement nor a different limit, but is fully equivalent with the general requirement, provided that the retinal irradiance profile is circular and homogenous and provided that the measurement is performed with an open FOV. If the relationship of the two is not fully appreciated, then it can appear that the specifications in IEC 60825-1:2014 are not fully consistent with the 2013 ICNIRP guidelines.

We do acknowledge that the discussion in the 2013 ICNIRP laser guidelines on this issue is somewhat short, but we would argue that all the relevant information is available; additional information and discussion is available in the literature (for instance [3, 6, 26, 27, 29, 31]).

It is also important not to "mix" the two concepts in one viewgraph as the limits then appear inconsistent (such as in figure A.8 of AKNIR Statement [25]). The presentation, for the case that the apparent source is a top-hat profile larger than α_{max}, should be either in terms of limited C_E (noting that the exposure level is also limited to the part that is within an angle of acceptance equal to α_{max}) or the presentation should be with an α^2-formulation (C_E^{open}) but emphasizing that the measurement is to be performed with an open FOV and that this presentation is accurate only for top-hat profiles, see Figure 7. This information is unfortunately also missing in the European workplace safety directive for artificial optical radiation AORD [32], where the α^2 formula is given without information on limitations.

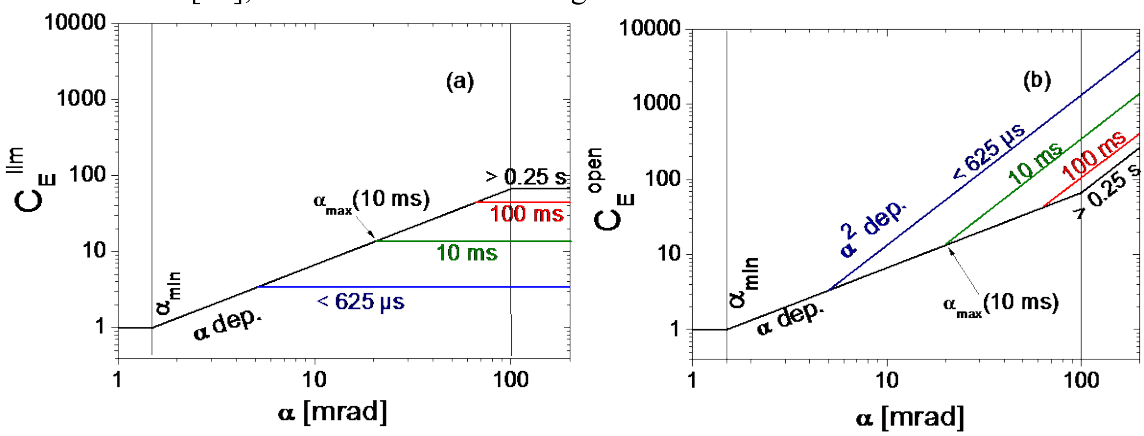

Figure 7. Examples of the correction factor C_E for retinal thermal exposure limits for extended sources; in a) the factor is limited to α_{max} / α_{min} but the measurement angle of acceptance is also limited to α_{max}; in b), the effect of the angle of acceptance to reduce the exposure level is accounted for by increasing C_E beyond α_{max}, but then the measurement needs to be performed with an open field of view.

6. Far IR Corneal Limits

In publications by BAuA [33] and a task group of the German society AKNIR [25] the concern is voiced that the EL equal to 1000 W m^{-2} for wavelengths larger than 2600 nm, for exposure durations longer than 10 seconds is too high because it is perceived to be based on the assumption of aversion responses. This misunderstanding is probably prompted by the first sentence in the ICNIRP guidelines [1] as reproduced below.

> If exposures approached 1000 W m^{-2} for a second or two, there would be an almost immediate sense of heating of the cornea leading to blinking and rotation of the eye. The infrared corneal aversion response requires further study before user safety requirements are relaxed, but the extreme rarity of infrared laser corneal injuries in the workplace clearly suggests that the corneal aversion response may provide significant protection.

Critical statements overlook that in the next sentence it is stated that more research is needed *before* safety requirements are relaxed, i.e. before the limits or the averaging aperture can be increased. This second sentence basically states that the current ELs in the far infrared are *not* based on an aversion response. This conclusion can also be drawn from thresholds published in the scientific literature.

The corneal injury threshold for a 10 second exposure for a strongly absorbed wavelength (such as 10.6 µm) for a **stationary eye** and large beam diameters (worst-case) is equal to 20 000 W m^{-2} [34]; ***thus the reduction factor is 20***. While, for longer exposure durations, the exposure limit remains constant at 1000 W m^{-2}, the injury threshold, for a stationary eye, reduces somewhat. Injury thresholds of the cornea can be modelled very well with a computer model [35, 36]; the model predicts that the injury threshold is above 10 000 W m^{-2} even for 100 s exposure duration for a 6 mm beam at the cornea, without any eye movements. Therefore, due to the large reduction factor at 10 seconds, the EL is still well below the injury threshold for unrealistically long exposure durations of a stationary eye. That is, it does not matter if there is an aversion response or not, the safety of the cornea is assured by the conservatively low EL, even for intentional long term exposure of an immobilized eye and a stationary beam.

While the references discussed in the AKNIR statement on perception and aversion response are highly interesting, the ICNIRP guidelines clearly state "*before* user safety requirements are relaxed.". We also invite to consider actual injury threshold studies and trends for the stationary eye [34].

Although warming will be perceived for a highly absorbed wavelength at the level of 1000 W m^{-2}, the stimulus, as the literature review in the AKNIR statement also showed, might be insufficient to invoke a reliable aversion response. However, the concern in the AKNIR statement is not applicable, because exposure below the current EL prevents injury even for the case that there is no aversion response, as was shown above. In fact, based on well characterized injury thresholds, the EL could be increased to for instance 5000 W m^{-2} for exposure durations of 10 seconds and would still provide adequate protection with a reduction factor of larger than 4 even for an immobilized eye (i.e. for the case of no aversion response).

7. Conclusions

Some of the exposure limits recommended by ICNIRP are quite complex. Not only the limits themselves need to be considered, but also recommendations for limiting apertures to average the exposure level that is compared against the EL. For the retinal thermal and photochemical limits, for extended sources, it is important to recognise the role of the defined angle of acceptance γ_{th} and γ_{ph}, respectively. However, it is also important to recognize that almost all potentially hazardous laser exposures occur from point sources, where the exposure guidelines require fewer correction factors and complex measurements or calculations. This is the default condition for laser radiation. By contrast, the incoherent-source guidelines have large sources as the reference EL that is expressed as a radiance, where source-size correction factors are applied for smaller sources.

It is not in the scope of the ICNIRP guidelines to discuss radiometric principles nor to discuss how in practice the determination of the exposure level is performed. The interested reader, and particularly the critical reader of the ICNIRP guidelines is invited to consult other publications on these aspects. The ICNIRP guidelines cannot contain all the information required to conduct a safety analysis in practice.

The issues discussed in this proceeding paper are either stated in the ICNIRP guidelines (in a succinct way) or are found in other publications, which are also referenced in the ICNIRP guidelines.

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