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Abstract

In order to perform a quantitative laser safety analysis, it is necessary to compare the exposure limit (EL) for the eye or the skin with the expected exposure level in terms of irradiance or radiant exposure. The exposure level, however, is not necessarily the actual physical irradiance or radiant exposure, but is a value that is averaged over an aperture with a defined diameter. When the laser beam is smaller than the averaging aperture, the resulting "biologically effective" irradiance or radiant exposure value is much smaller than the actual value.

The background of the averaging aperture sizes that are specified is discussed together with the ELs for laser radiation. For the wavelength range where the retina is at risk (400–1400 nm) the diameter of the averaging aperture is 7 mm. This aperture is be used to average the irradiance that is incident at the level of the cornea. Since the EL in this wavelength range is also given as irradiance and referenced to the position of the cornea, the concept of averaging apertures is cohesive; however, it is not intuitive and it is difficult to convey in training courses, and is often the reason for miscalculation.

An alternative, more straightforward dosimetry concept is proposed, where the EL is transformed into a "power" value by multiplication by the area of the averaging aperture. This procedure results in values which are identical with the accessible emission limits for Class 1 of IEC 60825-1. For the safety analysis, this EL (for instance 1 mW) is compared to the power that passes through an aperture with a diameter of 7 mm. This alternative concept is mathematically equivalent to the currently defined concept; however, in contrast to the present dosimetry concept, it is intuitive because the exposure value that is compared to the EL can be understood as "power that passes through the pupil of the eye".

Keywords: Laser; Exposure limit (EL); Maximum permissible exposure (MPE); IEC 60825-1; ICNIRP; Averaging aperture; Limiting aperture; Dosimetry; Retinal injury

Introduction

In order to answer the question "Is a potential exposure to laser radiation safe?" the exposure level at the eye or the skin (that is measured or calculated) needs to be compared to the respective exposure limit (EL). If the exposure level is below the EL, the exposure is considered "safe". If the exposure level exceeds the EL, safety measures, such as eye protection or organizational procedures, need to be implemented. It is unique to laser safety that the exposure level is, in many cases, not the actual physical level that is incident on the eye or the skin, but some "effective" value that is determined according to specific rules. If the rules as to how the exposure level is to be determined are not observed, the safety analysis can err by several orders of magnitude. This paper concentrates on the role of the "averaging aperture" that is used to determine the irradiance or radiant exposure that is subsequently compared to the EL. A more detailed discussion on other relevant parameters, including the role of the field of view for determination of the exposure level for extended sources, is for instance given by Henderson and Schulmeister [1].

Terms and definitions

Documents that define ELs

Exposure limits for laser radiation for the eye and the skin are, on the international level, developed by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) which reviews available injury threshold data and, with an appropriate reduction factor (formerly referred to as safety factor), sets ELs. The ELs that are defined by ICNIRP and published in Health Physics [2,3] are not legally binding but are a recommendation given by a committee of experts. The ELs become binding, however, when they are adopted by national legislation, such as in Europe for exposure at the workplace when the Directive on Artificial Optical Radiation [4] is integrated in national workplace safety laws in 2010. The ICNIRP ELs are also copied by the IEC and published for information only (i.e. also non-binding) in the laser classification standard IEC 60825-1 [5] (in Annex A) and in the Technical Report IEC TR 60825-14 [6], a guide for laser users. All of these sets of ELs are identical (since they originate from ICNIRP), the difference lies in the presentation as well as the terminology: while ICNIRP refers to "exposure limits", the European Directive uses the term "exposure limit values" (sometimes only "limit values"), and IEC documents use the term "maximum permissible exposure" (MPE). In the USA laser ELs are developed independently of ICNIRP where, specifically for the work-place, the American Conference of Governmental Industrial Hygienists (ACGIH) publishes their "threshold limit values" (TLV®) for laser exposure of the eye and skin [7], and the ANSI standard Z136.1 [8] gives guidance on user safety measures using the term MPE. The ELs given in the US documents, however, are almost identical to the ELs set out by ICNIRP. This is with the exception of revision processes, where one committee might be "faster" then another, such as is currently the case for the ACGIH TLV® that are already revised while ICNIRP is to publish its revision in 2010, and IEC not before 2011. The dosimetry concepts discussed in this review, being an inherent part of the ELs for laser radiation, are the same for the above mentioned documents.

Quantities and units

Table 1 lists quantities, units and the usually associated symbols as standardized by IEC/CIE [9,10] that are used to express both the ELs and exposure levels for laser radiation. For low level laser therapy (LLLT), instead of irradiance and radiant exposure, often the term "power density" or "energy density" is used. Power density, however, is internationally standardized to describe power per volume (in units of W/m^3), not power per area. Also the term "intensity" is often used erroneously instead of the correct term "irradiance"; intensity is standardized to quantify the power per solid angle (in units of W/sr).

Table 1 is organized in two blocks: the left block lists the "power" units; the right block the equivalent "energy" units. The relationship between power and energy in its simple form (not using integrals) is via multiplication by time, i.e.

$$Energy = power \cdot time \qquad (1)$$

where "time" can be the pulse duration or the exposure duration. Both the ELs and the exposure level can be expressed either in terms of "power" units or of "energy" units;

Table 1. Quantities relevant for the expression of exposure levels and ELs for laser radiation (German in brackets).

	"Power" units			"Energy" units		
	Quantity	Symbol	Unit	Quantity	Symbol	Unit
Basic quantity	Power (Leistung)	*P*	Watt	Energy (Energie)	*Q*	Joule
"Averaged over aperture area"	Irradiance (Bestrahlungs-stärke)	*E*	W/m^2	Radiant Exposure (Bestrahlung)	*H*	J/m^2

as long as the transformation via time is consistent, the two are equivalent.

These "temporal" aspects of laser safety dosimetry are not further discussed here (see for instance [1,11] for further discussion). All the "spatial" aspects of dosimetry, that are the main topic of this paper, apply in the same way to the "power" values as they do to the "energy" values. Therefore, in the remainder of the paper, when spatial dosimetry aspects of the "power" quantities are discussed, the same holds for the equivalent "energy" quantities.

Methods: Averaging irradiance

Basic principle

The ELs "limit" the exposure of the relevant parts of the human body, namely the eye and the skin, to a safe level. It can be easily seen that it is not only the radiant power of the laser beam that is relevant for the interaction with tissue, but also over which area this power is distributed. The appropriate quantities to quantify exposure of a surface to optical radiation are therefore irradiance and radiant exposure, as given in the second line of Table 1. As the ELs for laser radiation are expressed in terms of irradiance or radiant exposure, also the exposure level of the eye or skin that is to be compared to the EL needs to be expressed in terms of irradiance or radiant exposure. It is the main point of this paper to emphasize that the irradiance (and radiant exposure) value that is compared to the EL is not necessarily the actual physical value. However it can be an averaged value which can be orders of magnitudes smaller than the actual "true" physical irradiance or radiant exposure, this latter term not being specifically mentioned in the following paragraph.

In order to discuss this averaging concept it is best to consider how irradiance is measured. A laser radiometer is typically calibrated to measure radiant power or energy incident on the detector with a given sensitive area. The sensitive area can also be reduced by an aperture of a given size. In the following, apertures or sensitive areas of the detector are assumed to be circular and both are referred to as the aperture. The irradiance (at a certain position in the laser beam) is determined by dividing the power, as measured with the radiometer, by the area of the aperture. If the irradiance profile incident on the detector is not spatially constant over the detector or aperture area, then the resulting irradiance value represents a value that is averaged over the area of the aperture. An example plot of a non-constant irradiance profile and the average value is shown schematically in Fig 1. The averaging can be conceptualized as "spreading" the total power on the detector over the aperture area. If the irradiance profile is constant across the aperture then the averaged value is equal to the actual irradiance. If the irradiance profile features hot-spots (localized irradiance maxima) or if the laser beam is smaller than the averaging aperture, the averaged value is smaller than the actual maximum irradiance value.

In the field of laser safety, specific averaging apertures are specified which are related to biological parameters such as pupil size and eye movements. For safety evaluations, it is this “biologically effective” value that has to be compared to the respective EL. If the actual physical irradiance value were to be compared with the EL, the analysis might be severely over-restrictive.

Regarding terminology it is pointed out that while the ICNIRP refers to the respective apertures as “averaging apertures”, IEC documents refers to them as “limiting apertures”. The term “limiting” aperture appears to be less appropriate than “averaging” aperture when the apertures are defined to be used to average the exposure level. The term “limiting” would appear to be more appropriate for the case where the aperture is used to define the area over which the power is measured, limiting the measured “power” value to the part of the beam that passes through the aperture.

Averaging apertures

Table 2 lists the diameter of the averaging apertures as defined for the averaging of the exposure level that is to be compared to the ELs. For the eye, the diameter of the averaging aperture depends both on the wavelength of the radiation as well as on the pulse duration. The wavelength dependence is based on different injury mechanisms (photochemical in the ultraviolet (UV), thermal in the visible (VIS) and infrared (IR)) as well as different parts of the eye that are at risk. For the wavelength range of 400–1400 nm, the so-called “retinal hazard region”, the retina is at risk, whereas for longer and shorter wavelengths, the anterior parts of the eye are at risk. The pulse duration (or exposure duration) dependence reflects the influence of heat flow as well as movement of the eye relative to the beam to average out hotspots that are smaller than the averaging aperture. For short pulses, heat flow and eye movement has less effect and the respective averaging apertures are smaller than for longer exposure durations. For the skin, in the UV region and IR region above 1400 nm, averaging apertures are larger than for the eye, and take into account both scattering in the skin and a larger safety factor (reduction factor) inherent in the skin ELs. Also practical measurement issues play a role in the choice of the averaging aperture diameter: for wavelengths above 100 µm, the aperture needs to be 11 mm in order to minimize diffraction effects that would otherwise impede reproducible measurements. The use of the averaging aperture of 7 mm for the retinal hazard region (400–1400 nm) has different origins and is often the reason for incorrect analysis. This averaging aperture, however, is necessary for the system of “comparison of exposure level with EL” to work, as it is currently defined. The 7 mm averaging aperture can be understood when it is remembered that the exposure level is to be determined at the position of the cornea, while the actual tissue at risk is the retina which is not accessible for determination of the retinal exposure level.

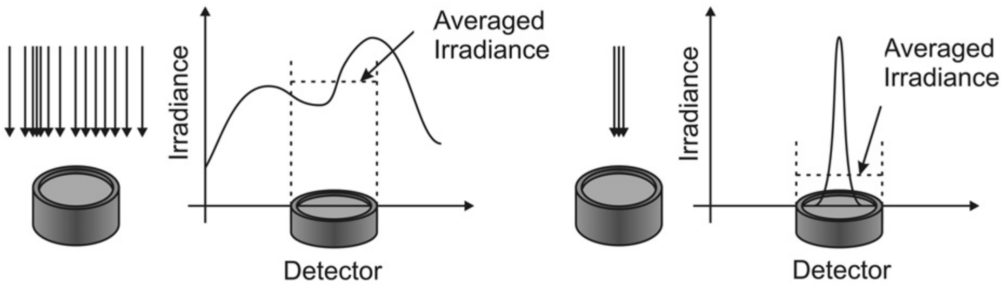

Fig. 1. Example of irradiance profiles across a detector surface, and the corresponding averaged value. Left: inhomogeneous profile; level of average irradiance depends on position of detector within beam. Right: a beam with a diameter smaller than the aperture – the averaged irradiance is much smaller than the real (peak) irradiance. Adapted from [1].

Table 2. Apertures as defined for averaging irradiance or radiant exposure to be compared to the ELs. In IEC 60825-1 these apertures are referred to as "limiting apertures".

Spectral region (nm)	Aperture diameter (mm)		
	Eye		Skin
180–400	1		3.5
≥ 400–1400	7		3.5
$\geq 1400–10^5$	1	for $t \leq 0.35$ s	3.5
	$1.5\ t^{3/8}$	for 0.35 s < t < 10 s	
	3.5	for $t \geq 10$ s	
$\geq 10^5–10^6$	11		11

Therefore, in terms of biophysical processes, it is not actually the irradiance at the cornea that is the relevant quantity, but rather the power that enters the eye through the pupil and that is incident on the retina. The basis of the averaging aperture of 7 mm is the maximum diameter of a dark-adapted pupil and is therefore the relevant dimension over which the irradiance is "biologically" averaged. While it might appear peculiar to divide the power of a beam with, for instance, a diameter of 1 mm by the area of the 7 mm aperture to obtain the exposure level, it has to be kept in mind that for a collimated laser beam the retinal spot will always be minimal, irrespective of the beam diameter at the cornea. This point is worth emphasizing – whether the beam diameter is 1 or 7 mm, as long as it is collimated, it will produce a minimal retinal spot (neglecting aberration that is much stronger for a dilated pupil).

The relevance of the 7 mm averaging aperture is demonstrated with the following example. Assuming the following:

(1) a laser beam produces an irradiated area on the cornea (and the power detector) of, for example, $A_{laser} = 1\ mm^2$, and

(2) the radiant power contained in this laser beam equals P = 0.1 mW, and

(3) the laser radiation is in the visible spectral range, and

(4) in front of the detector is an aperture with a diameter of $D_{7\ mm} = 7$ mm, corresponding to an area of $A_{7\ mm} = 3.8\ 10^{-5}\ m^2$

a radiometer calibrated in Watt would display a value of P = 0.1 mW – the total power in the beam (since the beam is smaller than the 7 mm aperture, the aperture as such actually does not influence the measurement). The average irradiance $E_{average}$ is obtained by dividing the power measured through the 7 mm aperture by the area of the 7 mm aperture, i.e $E_{average} = P / A_{7\ mm}$ which gives 2.6 W/m^2. The actual physical irradiance in the laser beam would be (for the simplifying assumption of a top-hat beam) P / A_{laser} (i.e. 0.1 mW divided by 1 mm^2), which equals 100 W/m^2, a factor of 40 larger than the averaged value. The irradiance value obtained by averaging over an aperture of 7 mm diameter is, however, the correct value to be compared to the EL of laser radiation.

For an assumed exposure duration of 0.25 s (applicable for unintentional exposure), the EL for a collimated beam (producing a small retinal spot) equals 25 W/m^2. While the correctly averaged value of 2.6 W/m^2 is a factor of 10 below the EL (the exposure is "safe"), if the true physical irradiance at the cornea had been used, the EL would erroneously appear to be exceeded by a factor of 4.

Discussion: Alternative, simple concept

As explained, the current method of determining whether an exposure in the retinal hazard region is "safe" is not intuitive and leads to errors so it might be worth considering a more intuitive approach by inverting the process. So instead of dividing the power that is measured through a 7 mm aperture by the area of the aperture to obtain an averaged irradiance, it is mathematically equivalent to transform the EL into a "power" value by multiplication by the area of the 7 mm aperture, and to simply compare the power that is measured through the aperture with this "power-EL". For visible radiation and exposure duration of 0.25 s, this produces a "power-EL" of 1 mW. If one places a 7 mm aperture in front of a power detector, or if the detector has a sensitive surface with a diameter of 7 mm, then the EL is exceeded when the power meter measures more than 1 mW. In this case, the nominal ocular hazard distance (NOHD, the distance where the EL is exceeded) is also simply determined by moving the detector along the beam until the beam diameter becomes so much larger than 7 mm that the power that passes through 7 mm is just 1 mW. The power that is measured with this concept is easily understood as the power that would enter the eye with a dilated pupil and would subsequently (with some absorption losses) be incident on the retina. Since this alternative concept is derived by multiplication of the current "irradiance-EL" by the aperture area (instead of dividing the power to obtain an irradiance-exposure level), it is mathematically equivalent to the current concept, as shown in Table 3.

Similarities and differences to Class emission limits

Since the emission limits for Class 1 and Class 2 as defined in IEC 60825-1 in the wavelength range of 302.5–4000 nm are derived from the ELs for the eye by multiplication by the area of the averaging apertures [1], the values of the "power-ELs" of the alternative concept are identical to the values for the accessible emission limit (AEL) for Class 1. However, although the numbers are equal and the procedure for the derivation is the same, the function of the two sets of limits is different and needs to be kept apart. The AELs limit the emission of a product for a given safety class, while the ELs for the eye and skin are human exposure limits. Product safety classes and AELs are defined by the Technical Committee TC 76 of IEC, while the ELs are defined on the international level by ICNIRP, and on the national level by legislature. And thirdly, the accessible emission to be compared to the AEL needs to be determined with specific rules (such as single fault conditions) and at distances defined relative to the product as defined in IEC 60825-1, while the exposure level to be compared to the ELs for the eye and skin are determined at the location of (potential) human exposure.

In principle the "power-EL" concept could also be used for the wavelength range outside of 400–1400 nm, i.e. where the anterior parts of the eye are at risk, or even for skin exposure. In all cases, the power determined through the "limiting aperture" (Table 2) would have to be compared to an EL that was derived by multiplying the current "irradiance" value by the area of the limiting (averaging) aperture. However, this is counterintuitive for the case of surface absorption, where the current concept is more appropriate. It is of note that for wavelengths less than 302.5 nm and above 4000 nm, where optical instruments cannot increase the accessible emission, even the AELs are specified in terms of irradiance and radiant exposure.

Direct comparison with experimental injury threshold values

The presentation of the EL for the retina in terms of "power" values also has the advantage that these values can be compared directly with experimental

Table 3. Demonstration of mathematical equivalence of current and simplified "power" presentation of the ELs and the exposure level.

	Current concept	Alternative concept ("power-EL")
Exposure level definition and units	Irradiance averaged over 7 mm aperture (W/m^2)	Power passing through 7 mm (W)
Exposure level measurement	Power passing through 7 mm ($P_{7\,mm}$) divided by aperture area ($A_{7\,mm}$): P_{7mm}/A_{7mm}	Power passing through 7 mm: $P_{7\,mm}$
Safety analysis (mathematical expression)	$P_{7mm}/A_{7mm} < EL_{irradiance}$?	$P_{7\,mm} < EL_{irradiance} \cdot A_{7mm}$?
Example of EL*	$EL_{irradiance} = 25\ W/m^2$	$EL_{irradiance} \cdot A_{7mm} = 1\ mW$

threshold data for laser-induced retinal injury, which are generally specified in terms of "intraocular power" (or energy). The intraocular power is the power that is incident on the eye and subsequently passes through the pupil of the experimental animal, and, with some absorption losses, is finally incident on the retina. A representation of the EL in terms of power and a direct comparison with experimental threshold data was, for instance, used in another paper of this special issue [12].

Analysis of "extended sources"

To present the retinal ELs in the quantities of power or energy, and the exposure level in terms of "intraocular power" or "intraocular energy" (i.e. the power or energy passing through a 7 mm aperture) is also advantageous when it comes to perform a safety analysis for the case that the retinal image is extended, i.e. larger than a minimal retinal spot. The default condition for laser radiation is a minimal retinal spot and usually it is not necessary to perform a more complicated analysis of the retinal image. However, for special sources such as multiple sources, diffused sources or line lasers, for an accurate analysis it is necessary to consider the distribution of the power over the retinal image, i.e. the retinal irradiance profile. The retinal thermal EL for such "extended sources" depends on the angular subtense of the apparent source (α) [1,13]. This parameter can be understood as "thermal diameter" of the retinal irradiance profile [14]. In IEC 60825-1:2007 [5], a method to determine α for arbitrary retinal profiles was included that requires to analyze different parts of the image and to determine the most restrictive (maximum) ratio of the power within a given part of the image over the "diameter" α for that part. This method was described 2004 by Henderson and Schulmeister in [1] and is an extension of the method proposed by Hollins et al. 1999 and referred to as the "encircled energy method" [15]. Schulmeister et al. [14] proposed to refer to the method as "most restrictive ratio" (MRR). Experimentally, the method is applied by using an "artificial" eye with a lens to simulate the cornea and lens of the eye and to produce an image on a charge-coupled device (CCD) array. The signal of each pixel of the CCD array is a measure of the radiant power incident on that pixel. The radiant power contained in parts of the image is simply obtained by summing up the signals of all the pixels that are located within that partial image. For the MRR method, the size and position of the partial area is varied and for each partial image, the partial power is divided by the parameter α that is associated with that partial image. The partial image for which the ratio of partial power over α has the maximum value is the critical image. The partial power for this critical image is then used to be compared to the EL (i.e. is the effective exposure level), where the EL was calculated with the angle α associated to the critical partial image. Since the total power that is contained within the retinal image is nothing other than the intraocular power described above, it is clear that the MRR method is much more straightforward to apply when the retinal thermal EL is given in terms of power or energy rather than in terms of (corneal) irradiance or radiant exposure. It is possible to apply the MRR method also to the present dosimetry concept (where ELs are expressed as corneal irradiance) by dividing the partial power by the area of the 7 mm averaging aperture to obtain an averaged irradiance value. This "irradiance" value would then constitute a partial averaged irradiance (compared to the total averaged irradiance) that is incident on the cornea. However, the concept of a partial corneal irradiance to characterize the power of a partial retinal image is misleading, or at least difficult to conceptualize, because the corneal irradiance is not directly related to the retinal irradiance profile.

Summary and conclusions

The concept of determination of the exposure level of the eye or skin by averaging over a specified aperture was discussed. For laser beams that are smaller than the averaging aperture, this produces "effective" exposure levels that are smaller than the actual true physical value. A special role is played by the averaging aperture that is to be used for radiation in the wavelength range of 400–1400 nm for exposure of the eye. In this wavelength range it is the retina which is at risk, but the ELs are defined in terms of irradiance at the cornea which is averaged over a 7 mm aperture, derived from the 7 mm diameter of a dilated pupil. It is important to consider the potential impact of averaging apertures, particularly the 7 mm aperture, in any laser safety analysis. To refer to ELs without emphasizing the role of the averaging aperture could lead to a safety analysis that errs by several orders of magnitude.
An alternative concept of determining the exposure level and presenting the ELs for retinal hazards – in terms of power through a 7 mm aperture – is given. While the results of this alternative concept are identical to the current one, it is easier to understand and to teach than the current concept which relies on averaging irradiance over an aperture. To express the ELs that relate to retinal injury in terms of power also has the advantage of being consistent with the new method to analyze the potential thermal hazard of "extended sources", where the partial power (or energy) that is contained in the critical part of the retinal image is compared to the retinal thermal EL.

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Zusammenfassung

Derzeit gültige und alternative Konzepte der Mittelungsblenden für Laser-sicherheitsanalysen

Zur Durchführung einer quantitativen Lasersicherheitsanalyse ist es notwendig, den Grenzwert für die Bestrahlung der Haut oder des Auges mit einem entsprechenden Bestrahlungs- oder Bestrahlungsstärkewert zu vergleichen. Die Bestrahlung, die mit dem Grenzwert zu vergleichen ist, ist jedoch nicht notwendigerweise die wirkliche physikalische Bestrahlungsstärke, sondern stellt einen über eine Blende mit bestimmtem Durchmesser gemittelten Wert dar. Für den Fall, dass der Laserstrahl kleiner als die Mittelungsblende ist, ergeben sich dadurch „biologisch effektive" Bestrahlungswerte, die viel kleiner sind als

die wirklichen Bestrahlungsniveaus. Der Hintergrund der gemeinsam mit den Lasergrenzwerten definierten Mittelungsblenden für Auge und Haut wird besprochen. Für den Wellenlängenbereich, in dem die Netzhaut betroffen ist, ist der Durchmesser der Mittelungsblende 7 mm. Diese Blende muss benutzt werden, um die Bestrahlungsstärke am Ort der Hornhaut zu mitteln. Da der Grenzwert für das Auge auch in diesem Wellenbereich als Bestrahlungsstärke gegeben ist und auf den Ort der Hornhaut bezogen ist, ist das Konzept der Mittelungsblenden zwar in sich schlüssig, jedoch nicht intuitiv und schwer in Sicherheitsausbildungen zu vermitteln, sowie häufiger Grund für unkorrekte Berechnungen.

Es wird ein alternatives Konzept vorgeschlagen, bei dem der Grenzwert durch Multiplikation mit der Fläche der Mittelungsblende in einen Leistungswert umgerechnet wird, was identische Werte zu den Grenzwerten für die zugängliche Strahlung für die Klasse 1 laut IEC 60825-1 liefert. Für die Sicherheitsanalyse wird dann dieser Leistungs-Grenzwert (z.B. 1 mW) mit der Leistung verglichen, die durch eine Blende mit 7 mm Durchmesser tritt. Dieses Konzept liefert identische Resultate zum derzeit definierten Dosimetriekonzept, ist aber insofern intuitiv, als dass der Expositionswert, der mit dem Grenzwert verglichen wird, die Bedeutung „Leistung, die durch die Pupille ins Auge eintritt“ hat.

Schlüsselwörter: Laser; Grenzwert; Maximal zulässige Bestrahlung (MZB); IEC 60825-1; ICNIRP; Mittelungsblende; Grenzblende; Dosimetrie; Netzhautschädigung

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