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Measurement of Optical Radiation to Assess the Blue Light Hazard

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Abstract

For the safety assessment of optical broadband radiation, separate limits are given for thermal and for blue light hazard to the retina by ACGIH and ICNIRP.
For small sources, the blue light limit is given as a radiant exposure limit in J/m², however for extended sources the basic limit is specified as radiance in J/m² sr. For the measurement of radiance, the size of the field of view (FOV) of the measurement detector is an important factor, as the radiation is averaged over the FOV, even if the source size is smaller than the field of view. Limits given in radiance can be transformed into irradiance limits by multiplying the radiance limits by the corresponding measurement FOV. For photobiological limits it is important to note that the measurement FOV corresponds to the extent of eye movements and is therefore time dependent.
In the latest draft for the revision of the international laser safety standard, IEC 60825-1, and in the revised ICNIRP laser limits, blue light limits are split from the thermal limits and are given in irradiance, specifying corresponding measurement criteria for the measurement FOV. This paper will discuss the derivation of the irradiance blue light limits from the broadband radiance limits and will discuss the importance and applicability of a well defined measurement FOV.

Introduction

For damage of the retina by optical radiation, two interaction mechanisms can be distinguished: photochemical and thermal damage. In table 1, the basic differences are summarized.

Table 1 Principal features and differences of thermal and photochemical damage mechanism

	Thermal	***Photochemical***
Wavelength band	380 – 1400 nm	principally 380 nm – 550 nm
Wavelength dependence	absorption dependence	action spectrum
Time domain	principally pulses and short exposures (< 10s)	longer exposures (> 10 s)
Dependence on image size	larger image, smaller exposure limit	none
Additivity	none	additive up to 10,000 s

So far, only one "combined" ocular laser exposure limit existed[1] and the differentiation between the two competing damage mechanisms was only realized by the exposure limits for broad-band incoherent optical radiation, as published by ICNIRP[2] and ACGIH[3]. Recently, ICNIRP was prompted to review the laser exposure limit guidelines and has subsequently recommended to split the ocular exposure limit into dual limits: one for photochemical and one for thermal injury[4]. As the laser limits published in IEC 60825-1 are based on the ICNIRP limits, the revised laser limits will also be contained in the next edition of IEC 60825-1, which is currently in the draft stage[5]. In this paper, the laser exposure limits for photochemical damage, also termed "blue-light hazard", and the associated measurement requirements will be discussed.

Broadband Limit and Measurement

The broad-band exposure limit for the blue-light photochemical retinal hazard is given as[3]:

$$L_B \cdot t \leq 10^6 \, \frac{J}{m^2 \; sr} \tag{1a}$$

where L_B is the effective blue-light radiance at the eye and t is the exposure duration.
For t > 10,000 s:

$$L_B \leq 100 \, \frac{W}{m^2 \; sr} \tag{1b}$$

The term „effective" indicates that the spectral radiance L_λ of the broadband source is weighted with the blue light hazard action spectrum $B(\lambda)$ and is subsequently integrated over the wavelength λ:

$$L_B \cdot t = \sum_{300}^{700} L_\lambda \cdot B(\lambda) \cdot t \; \Delta\lambda \tag{2}$$

The measurement of irradiance, as it is generally known for laser hazard measurements, can be seen as first step of the radiance measurement (in units of W m^{-2} sr^{-1}), where the irradiance value is subsequently divided by the field of view of the measurement set-up to determine the radiance (see also Fig. 1).

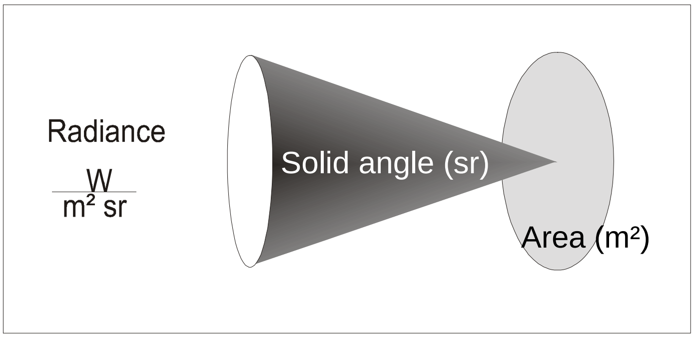

Fig. 1. For hazard measurements, radiance can
be seen as the irradiance at the detector (averaged over a 7 mm diameter aperture)
divided by the field of view of the detector as measured in steradian.

The Field of view (FOV) of a detector or of the input optics corresponds to a certain angle which is "seen" by the detector, or, out of which the detector receives radiation. The field of view is either defined as the "two-dimensional" solid angle measured in steradian or the full plane angle measured in radian; the term *angle of acceptance*, is also often used, more often for the definition as plane angle than for the solid angle.

A well defined FOV can be obtained by either of two set-ups, which are depicted in Fig. 2 and Fig. 3. Assuming a circular FOV, in both set-ups the size of the FOV is determined by the size and location of the circular field stop. The FOV can be defined either by placing the field stop at the source and the detector at a corresponding distance (see Fig. 2), where the plane angle - FOV (in units of radian) is given by the ratio of the diameter of the field stop to the distance of the field stop to the aperture stop. This set-up relies on the placement of the field stop at the source or very close to the source, which means that the source has to be accessible. However it allows to use radiometers with detectors or input optics with a large FOV, which are usually used to measure irradiance. The deliberations regarding the irradiance measurements in respect to the averaging over the aperture area - for the case of the blue light hazard over an aperture with a diameter of 7 mm - apply here to the aperture stop.

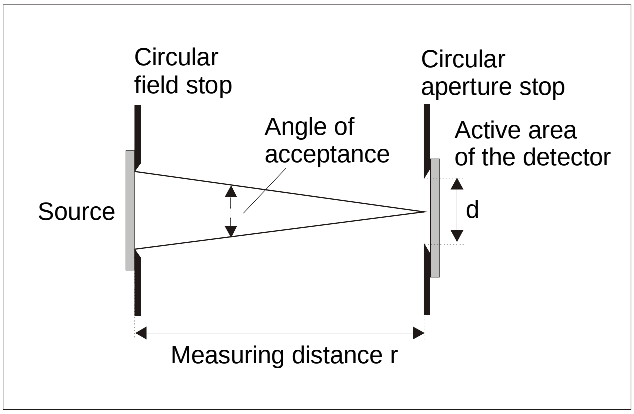

Fig. 2. A well defined field of view can be attained by placing the field stop at the source.

By imaging the source onto the field stop (Fig. 3), the field stop does not have to be placed at the source and therefore this set-up can also be used to measure sources which are not accessible. In order to define a FOV, a lens is used to image the source onto the plane of the field stop. The plane angle FOV is determined by the ratio of the diameter of field stop to the distance of the field stop to the lens. In this case, the averaging measurement aperture for the determination of the irradiance part of the radiance measurement is in front of the lens.

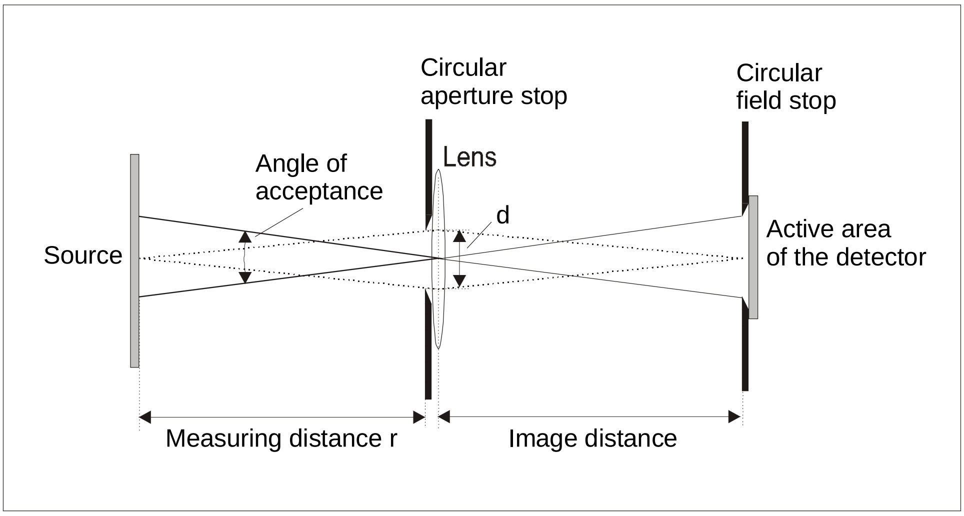

Fig. 3. As the source is imaging onto the field stop in front of the detector, a telescopic set-up can also be used for sources which can not be accessed.

Just as the irradiance measurement is averaged over the averaging aperture (of 7 mm diameter for the blue light hazard), so is the radiance measurement averaged over the FOV: as the FOV can be thought of as specifying the area of the source which is “seen” by the detector, the radiance is averaged over this part of the source. Hence if the source exhibits inhomogeneous emissions over areas smaller than the area seen by the detector, then the measured radiance will be a value averaged over the FOV. For the case of an angular subtense of the source which is smaller than the FOV, the FOV will be “underfilled” and the radiance averaged over this FOV will be smaller than the actual physical radiance (or “brightness”) of the source. This in direct contradiction to one of the maxims of radiance measurement, i.e. that the FOV has to be "overfilled" by the source. For instance, a source with a diameter of 5 mm subtends an angle of 5 mrad at a distance of 1 m. If such a source is averaged over a FOV of, say 100 mrad, the averaged radiance will be a factor 400 *smaller* than the actual physical radiance of the source. However for hazard evaluations, the value averaged over a specified FOV, which might be as large as 100 mrad, is what is to be compared to the respective exposure limit. Just as the irradiance hazard measurement is averaged over a specified minimum area which might be *larger* than hotspots or the beamsize at the irradiated plane, the radiance hazard measurement is averaged over a specified FOV which might be *larger* than the source. The rationale for the specification of the size of the averaging FOV is presented in the following.

Minimal Image Size and Eye Movements

For the hazard to the retina, not only the total power entering the eye is important, but also the size of the irradiated retinal area, i.e. the irradiance at the retina. If the eye is assumed to be resting in respect to a source, the diameter of the image on the retina d_r, in µm, can be related very easily to the angular subtense of the source α in mrad (see Fig. 4) by using the standardised focal length of the eye of 17 mm:

$$d_r = \alpha \cdot 17 \qquad (3)$$

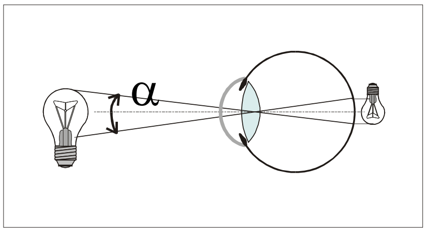

Fig. 4. The angular subtense of the source is directly related to the size of the image on the retina.

Although there is a geometrical equivalence of the telescopic radiance measurement with the image formation in the eye – and this is the reason why exposure limits for the retina are best expressed in radiance – it is important to note that the FOV is a property of the radiometer, whereas the angular subtense of the source, α, is a property of the source.

Due to the physical limitations of the imaging process in the eye, the minimal angular subtense of the image or spot-size on the retina, termed α_{min}, is about 1,7 mrad, which is equivalent to a spot size on the retina of about 25 - 30 µm. Such a minimal spot size can be realised either by a very small or distant source or by a well collimated laser beam, which, due to the parallel rays, is perceived as originating at a great distance from the viewer.

For exposure to flashes of light, the retina appears to be resting in respect to the image on the retina, and the angular subtense α, with a minimal value of α_{min}, can be used to estimate the size of the irradiated area on the retina and the corresponding irradiance. For continuous exposure situations, however, eye-movements will result in the movement of the image on the retina, causing the irradiated retinal area to be larger than the optical image size α, as is schematically depicted in Fig. 5. The extent of the eye-movements is time dependent: for very short exposures, the retina will be fixed in respect to the image for the duration of the exposure. With increasing exposure duration, eye-movements will increase from involuntary tremors to larger, task oriented eye-movement and for very long exposure durations under realistic situations, even head movements would come into play.

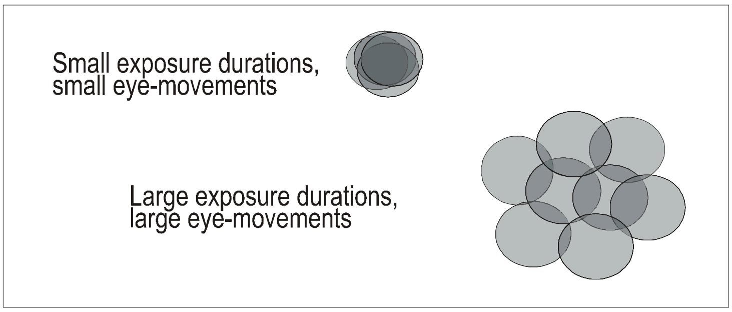

Fig. 5. In this diagram, the image on the retina is represented by a grey disk, and the eye movements are visualised by the location of the image at given time intervals. Eye movements will result in relative motions of the image over the retina, comparable to a photographic film being moved in relation to the image. This however distributes the radiant energy over a larger area, thereby decreasing the hazard.

Such eye-movements will increase the effectively irradiated and therefore also the potentially damaged area on the retina. However due to these eye-movements and the correspondingly increased irradiated area, the *effective* irradiance on the retina as defined by the power entering the eye divided by the effectively irradiated area, will decrease correspondingly, thereby decreasing the level of hazard as compared to the irradiation of a fixated eye for the same exposure duration. The general tendency is:
longer exposure duration $\Rightarrow$ larger eye movements $\Rightarrow$ larger effectively irradiated area $\Rightarrow$ smaller effective irradiance $\Rightarrow$ decreased hazard

Usually, if the level of the hazard is decreased, this is expressed by increasing the exposure limit, allowing for a higher exposure level. For the case of a decrease of the hazard due to eye-movements, this relaxation is not expressed as increase of the exposure limit as given in radiance, but by an increase of the averaging FOV. As discussed above, if the FOV is larger than the source, then the measured radiance value will be smaller than the actual physical radiance of the source. An increase of the averaging FOV results in a decrease of the effective radiance measurement value, as this value is derived by division with the averaging measurement FOV. Thereby the decrease of the hazard is not reflected by an increase of the exposure limit, but by a decrease of the measured effective value which is to be compared to the exposure limit. The specification of an averaging FOV results in the measurement of a *biologically effective* radiance value, which might be smaller than the physical radiance value of the source. Therefore, the effective radiance value should be seen as a parameter related to the *exposure* of the retina rather than as a property of the source.

It is suggested here that the Greek letter γ is used to denominate the averaging plane angle FOV to prevent confusion with the source size α and with the minimal retinal spot size α_{min}. In the guidelines for broadband radiation[2,3], the averaging FOV is specified to be 11 mrad for exposure durations between 10 s and 100 s. It is difficult to quantify the minimal averaging effect of eye-movements for exposure durations greater than 100 seconds and up to 10.000 s, which is about 2 ½ hours. In the course of the current revision of the laser exposure limits, ICNIRP will specify a square-root dependence of the plane angle averaging FOV, γ, which translates into a simple linear dependence of the solid angle averaging FOV, Γ, on the exposure duration[1].

$$10\ s - 100\ s \qquad \gamma = 11\ mrad \qquad \Gamma = 10^{-4}\ sr \tag{4}$$
$$100\ s - 10.000\ s \qquad \gamma = 1.1\sqrt{t}\ mrad \qquad \Gamma = 10^{-4} \cdot t\ sr$$

[1] The relation between the solid angle and the plane angle is $\Gamma = (\pi/4)\ \gamma^2$.

The consequences of the averaging FOV for practical hazard measurements shall be discussed for two FOV sizes in relation to a small and a large source, as schematically shown in Fig. 6.

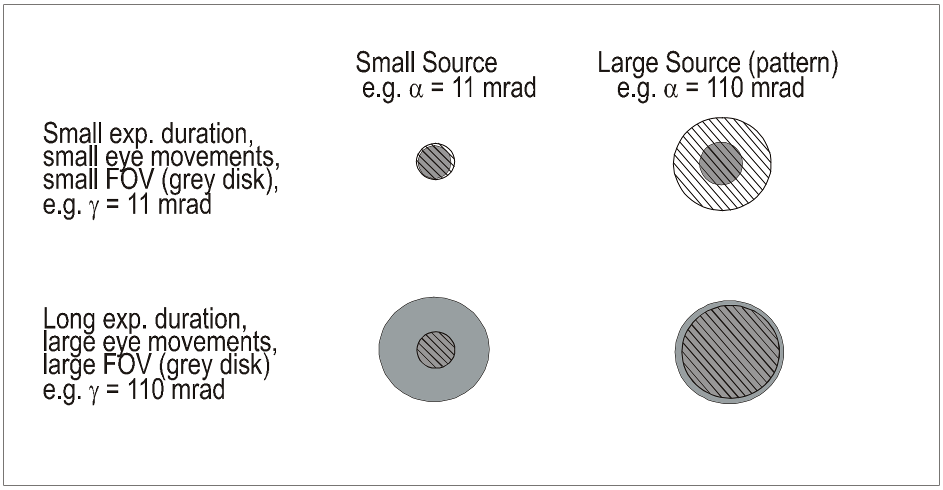

Fig. 6. Possible relations of source size to the averaging FOV as specified for two different exposure durations. If the source is smaller than the FOV, the measured averaged value is smaller than the physical value, if the source is larger than the FOV, the source will be sampled for hot-spots with the specified FOV.

For the example of a source size of α = 11 mrad, the averaging FOV for an exposure duration between 10 s and 100 s is γ = 11 mrad. For a homogeneous source, the measured effective radiance value will be the same as the physical radiance. If the same source is evaluated for longer exposure durations, the averaging FOV increases corresponding to increased eye-movements, thereby the *biologically effective* radiance value as averaged over γ is smaller than the real physical radiance of the source. On the other hand, for the case of a source of for instance α = 110 mrad, the specification of an averaging FOV of γ = 11 mrad means that the source is to be sampled for hot-spots. The examples also show, that for a given exposure duration the specified averaging FOV γ corresponds to a minimal image size, above which the effective averaged radiance is equal to the physical radiance, i.e. there does not seem to be a reduction in the hazard due to eye-movements for sources larger than γ. This can be understood on the basis of Fig. 7, where the image of a small and large source is represented by grey disks and for both sources the distribution corresponds to the same geometrical extent of eye-movements for a given time (i.e. the centres of the disks are at the same positions in both cases).

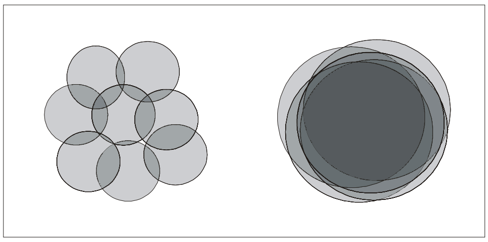

Fig. 7: Comparison of the effectively irradiated retinal area for the same extent of eye-movements for small and large source sizes: for large sources, i.e. images, the extent of the eye-movements is not large enough to significantly increase the effectively irradiated area.

If the extent of the eye-movements is small compared to the image size, then the irradiated area on the retina will correspond to the image size α. Therefore, for larger image sizes only larger eye-movements can significantly increase the effectively irradiated area on the retina.

Derivation of Irradiance Limits

The basic relation between radiance, L, and irradiance, E, is

$$E = L \cdot \Omega \qquad (5)$$

where Ω is the solid angle. This relationship appears simple, however due to the intricacies of optical radiation hazard measurements, care has to be taken when calculating irradiance exposure limits (ELs) out of radiance limits and when performing corresponding measurements.

The most straightforward case is a source with angular subtense α, which is smaller than the averaging FOV, γ. In this case, the measured effective radiance value does not depend on the angular subtense of the source, and it also does not depend on the actual value of the measurement FOV, as long as the FOV is larger than the source, and as long as the radiance value is obtained by dividing the irradiance value by the specified averaging FOV, Γ. Consequently the *radiance*-EL can be multiplied with the averaging FOV to obtain the exposure limit given as irradiance at the cornea, and the measurement can be performed with a regular irradiance detector with an "open", i.e. large, FOV. Specifically, this is done for the blue light limit, where the basic exposure limit is 10^6 W m^{-2} sr^{-1}. The exposure limit expressed as irradiance is obtained by multiplying with the appropriate averaging FOV Γ (see equation 5), i.e. with $\Gamma = 10^{-4}$ sr ($\gamma = 11$ mrad) for exposure durations from 10 to 100 s:

$$10^6 \text{ J m}^{-2} \text{ sr}^{-1} \cdot 10^{-4} \text{ sr} = 100 \text{ J m}^{-2} \qquad (6)$$

This value is specified for sources with angular subtense smaller than 11 mrad ("small" sources), which is the case for most laser sources. By multiplying the *radiance*-EL with the averaging FOV, the relaxation of the hazard due to eye-movements is contained in the exposure limit, which is not the case for the *radiance*-ELs, where the averaging is contained in the measurement value, which is to be compared with the *radiance*-EL. This relationship between the ELs and averaging FOV can be seen when the blue light *irradiance*-EL is derived for very long exposure durations[2], where $\gamma = 110$ mrad, i.e. $\Gamma = 10^{-2}$ sr:

$$10^6 \text{ J m}^{-2} \text{ sr}^{-1} \cdot 10^{-2} \text{ sr} = 10^4 \text{ J m}^{-2} \qquad (7)$$

A comparison with the value for exposure durations of 10 to 100 s shows, that the EL is larger for very long exposure durations. The relaxation of the hazard due to larger eye-movements results in an *increase* of the *EL*, if the EL is expressed as irradiance. For both evaluations, i.e. for 10 – 100 s and for very long exposure durations, the irradiance measurement value is the same, in contrast to the specification of the EL as a radiance value, where the value of the EL does not depend on the exposure duration, but the relaxation of the hazard is mirrored by a decrease of the effectively measured radiance value. It should be noted that the irradiance blue light limit is fully equivalent to the *radiance*-EL, provided that the radiance measurement is performed with the specified averaging FOV, and it is not a relaxation, as indicated in Reference 2.

The exposure limit for the blue-light hazard for exposure durations greater than 100 seconds up to 30,000 seconds can be given in a simple form when the exposure limit E_{EL} is derived from the radiance limit with the averaging field of view as specified in equation 4 and is subsequently divided by the exposure duration to obtain a value for irradiance:

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[2] At the time of writing it was not decided if the averaging field of view will be limited to 110 mrad or, as was previously defined, to 100 mrad. If an averaging field of view of 100 mrad is used, the limit would be 0.8 W m^{-2}.

$$E_{EL} = 1 \quad W \quad m^{-2} \tag{8}$$

It is mentioned above, that the irradiance limits are valid for sources smaller than the averaging angle, which implies that an "open"-FOV irradiance radiometer, as is common for laser measurements, is used for the hazard measurements. If the source were larger than γ, then one would measure a larger level of radiation, and the hazard would be overestimated as compared to the radiance-case, where the FOV is limited to γ. If the FOV for the irradiance measurement were also limited to γ, for instance by placing an aperture at the source, there would be a full equivalence to radiance measurements and the *irradiance*-ELs could also be applied to sources larger than γ. In this case however, γ is not an *averaging* FOV, but rather a *limiting* FOV, as it prevents that radiation from outside the FOV contributes to the measured irradiance. For the case that the source is homogeneous and an "open" field of view (i.e. larger than the source size α) is to be used, the exposure limits could be corrected for the larger measured value by increasing the exposure limit correspondingly:

$$E_{ELopen} = E_{EL} \cdot \alpha^2 \gamma^{-2} \tag{9}$$

If the source is not homogenous, this method would underestimate the hazard, as it would correspond to averaging over the source size, whereas the usage of the specified averaging field of view would be used to scan the source for hotspots, i.e. for maximised measurement values, which would have to be compared to the exposure limit.

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Meet the Author

Karl Schulmeister received his Dipl.-Ing. (1992) in technical physics from the Technical University Vienna and his M.Sc. (1994) in applied physics from Trinity College Dublin. He attended the Eurolaser Academy in Aachen in 1993. Since 1994 he is employed by the Austrian Research Centre Seibersdorf, where he is head of the „Laser and Optical Radiation" working group and accredited testing laboraties of the Department of Radiation Protection. In the last two years his research concentrated on UV-emission of high power laser beam welding and radiometry both for optical radiation hazard evaluation and laser safety. He is a member of CIE committees on lamp safety and on work-place safety assessment, and is the Austrian delegate to IEC TC 76 (Laser), where he is also Secretary of Working Group 1. He served as chairman for sessions at the International Radiation Protection Conference 97 in Vienna and at the International Laser Safety Conference 97 in Orlando. He is also involved with the ICNIRP task groups on laser and optical radiation hazards.

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