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Karl Schulmeister and Jan Daem

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BIOPHYSICAL DATA IN SUPPORT OF THE CLASSIFICATION DISTANCE FOR IMAGE PROJECTORS UNDER IEC 62471-5

Paper #301

Karl Schulmeister[1], Jan Daem[2]

[1] Seibersdorf Laboratories; Laser, LED and Lamp Safety Test House and Consulting; 2444 Seibersdorf, Austria
[2] BARCO NV Product Validation Group, 8520 Kuurne, Belgium

Abstract

According to the upcoming international photobiological safety standard for image projectors IEC 62471-5, the risk group of the projector is to be determined at a distance of 1 meter from the projector closest point of human access.

This document discusses biophysical data for Risk Group 2 (RG2) projectors which support the reference distance of 1 meter and in addition a risk analysis for exposure distances closer than 1 meter is provided. The analysis is based on the two main relevant parameters: the safety margin between injury threshold and emission limit, and the diameter of the pupil of the eye. The injury threshold for retinal thermal injury can be modeled well with the Seibersdorf Laboratories Injury Model and was calculated for the relevant wavelength distributions, retinal image sizes and exposure durations. The eye pupil diameter will be accounted for by data identified in the literature, considering that in order to accommodate to an apparent source at close distances, the pupil can be assumed to constrict due to the near triad of accommodation.

It is shown that the risk for retinal thermal injury from image projectors classified as RG2 under IEC 62471-5 can be considered as low to negligible.

Introduction

IEC 62471-5

In the past two years, a new safety standard for image projectors was developed by IEC TC 76, which is currently in translation as part of the FDIS stage: IEC 62471-5 is Part 5 in the standard series "Photobiological Safety of Lamps and Lamp Systems" and has the title "Image Projectors" (the current document reference is IEC 76/504/CDV [1]). It is thus a *vertical* standard, specifically developed for the safety of the skin and eye pertaining to optical radiation that is emitted from image projectors. In the scope of this standard are image projectors such as cinema projectors but also smaller data projectors. In the terminology of the IEC 62471 series, a "lamp" is distinguished from the "lamp system". For conventional projector, the lamp would be the xenon arc lamp or UHP lamp (which has to be regularly replaced and is the actual source of light) and the whole projector (housing, electronics, optical system and the lamp) is considered in the IEC 62471 series as the "lamp system". In terms of products used for lighting of rooms, the lamp system would be equivalent of the luminaire, which features one or more lamps (such as fluorescent lamps), but also reflectors, covers, electrical components etc. It should be noted that the risk group classification in the current edition IEC 62471:2006 [2] is defined in the strict sense only to apply to lamps and not to lamp systems. In Clause 6 of IEC 62471 "Lamp Classification" it is stated *"This clause is concerned with lamp classification. However a similar classification system could be applicable to luminaires or other systems containing operating lamps." that a similar risk group classification can be used for lamp systems as is defined for lamps."* Particularly, for lamp systems, the reference distance for classification is to be chosen, considering the specifics of the product type under test. The reference distance for classification is the distance from the product where the risk group is determined, i.e. where the emission level is compared against the emission limits for the different hazards and risk groups. For instance, if the emission level (or to use the laser classification terminology, the "accessible emission", AE) exceeds the emission limit (termed the accessible emission limit, AEL) for RG1, but is below the AEL of RG2, the product is assigned RG2. If the AE exceeds the AEL of RG2, it is assigned RG3.

At this point it should be noted that for consistency it is prudent to distinguish classification of a product (based on comparing AE and AEL at a defined reference distance) from an exposure assessment where exposure levels for the eye or skin are compared against exposure limits. Exposure assessments are being used for general safety analysis with variable exposure distances. While the AEL is typically numerically derived from (i.e. often equal to) exposure limits for the eye, it is different in concept as one characterizes the emission of the product at a defined distance to the product.

For lamps, IEC 62471 specifies a reference distance for General Lighting System (GLS) lamps as the distance where the illuminance equals 500 lx. For non-

GLS lamps, the reference distance is specified as 20 cm. As noted earlier, these reference distances are specified in IEC 62471 only for lamps, not for lamp systems, as lamp systems are specifically not in the scope of risk group classification of IEC 62471. Since an image projector is a lamp system (that for instance has a Xenon lamp as light source, which is under scope of the risk group classification of IEC 62471), it is necessary in a vertical standard such as IEC 62471-5 to define an appropriate classification distance for the specific lamp system in scope.

It was noted by the responsible expert group that the two reference distances that are used in IEC 62471 for lamps (the 500 lx distance and the 20 cm distance) are not appropriate for image projectors, as the 500 lx distance is too far away and the 20 cm distance is too close to appropriately reflect the risk. The main reason is that the AEL for retinal thermal injury is based on a 7 mm pupil diameter, which is overly restrictive for most exposure scenarios. In addition [3] as has been proven by many years of field experience, lower to medium power devices of a few thousand lumen output which are used on desks as consumer products - where exposure at close distance is reasonably foreseeable - did not produce any known detrimental effect on the retina. High power devices that employ very bright light source such as multiple kW xenon lamps or laser light requires specific form of installation. Examples are ceiling or cinema booth mounting. It is not reasonable to expect such device to be used in a home and uncontrolled environment due to minimum screen size requirements.

A user will seldom be exposed at close distance, this supports why a reference distance of 1 meter appeared more appropriate than 20 cm from the projection lens. However, since RG2 devices are considered as safe enough to be placed on the market as consumer devices (however, the more powerful units would be only high end systems and would only rarely be purchased by consumers), it needs to be shown that exposure at distances less than 1 meter is associated to an acceptably low level of risk.

Relevant Emission Limit

The critical emission limit for image projectors is the retinal thermal limit, i.e. the limit to protect against thermally induced retinal injury, where the usually assumed exposure duration (and therefore time base for classification) is 0.25 s, based on aversion response to bright light. Retinal thermal injury from non-laser sources is extremely rare as the brightness has to be so high that detrimental temperature increases are induced in the retina before the aversion response sets in, which is known only from nuclear blasts and intentional exposure to xenon arc lamps used for retinal surgery before the advent of the laser [4]. Also looking into the sun with telescopes can induce retinal thermal injury within a short exposure duration.

As previously noted the retinal thermal emission limit for a time base of 0.25 s is based on a pupil diameter of the eye with 7 mm, which is for most exposure scenarios overly restrictive. The assumed pupil size of 7 mm and the correspondingly low exposure/emission limit when expressed as radiance, for instance, results in the sun at moderate and high elevation angles to exceed the retinal thermal limit for 0.25 s by a factor of about 2 [5], (i.e. the sun when classified at the reference distance of the earth would be RG3 based on the retinal thermal limit) even though there is – as known from general experience – no risk for injury when looking at the sun for 0.25 s. Besides the assumed pupil diameter of the eye, there is a safety margin between the injury threshold and the emission limit, so that exceeding the emission limit (or the respective exposure limit) by some factor does not necessarily mean that there is a real risk for injury. This is for instance well known from laser products, where the exposure limit for 0.25 s for collimated laser beams in the visible wavelength range equals 1 mW, but from long time experience it is known that power levels up to 5 mW have basically negligible risk for thermal injury [6] and this range was also given a dedicated classification group, Class 3R.

The safety margin is not a well-defined or fixed number and depends on the wavelength (while the limit is constant in the visible wavelength range, the injury threshold is not), the retinal image size and the exposure duration (the injury thresholds feature a different dependence on exposure duration as compared to the emission limit); also there is some general uncertainty regarding the injury threshold that pertains to human exposure [7], as the data-set that is available has been obtained with non-human primates, mostly Rhesus monkeys. Human injury data is scarce but where it was compared against non-human primate data [8], the threshold for humans was higher than for non-human primates, even for heavily pigmented human retinas.

Risk Group 3 projectors are considered suitable only when installed or operated by professionals where additional safety means as installation requirements reduce the probability of users to be exposed at close distance (such as in a cinema booth with restricted access for untrained people). It is the combination RG3 projector operated by a professional or installed according to specific requirements that make the product safe to use. Risk Group 2 (RG2) is considered suitable as consumer and general office products. A warning is according to IEC 62471-5 as well as according to general product safety practice sufficient against prolonged staring into the product, but otherwise no special considerations regarding installation are considered necessary.

Since the retinal thermal emission limit for RG2 in IEC 62471-5 is directly derived from (numerically equal to) the 2013 ICNIRP revision [9] of the retinal thermal exposure limit for an exposure duration of 0.25 s, the reference distance of 1 meter means that as a worst-case scenario, the emission of an RG2 image projector equals the emission limit at 1 meter. This means that the exposure limit for the retinal thermal hazard for accidental exposure will be exceeded for exposure distances less than 1 meter. The distance where the exposure limit equals the exposure level is referred to as “hazard distance” (HD). An RG2 projector represents a lamp system having a HD of up to 1 meter. Generally spoken, RG2 image projectors with a HD of 1 meter typically have a corresponding output level exceeding 10000 lumens (for common projection lens parameters and imager size). These are correspondingly higher power projectors that are typically used in small cinemas or larger conference venues. If it can be demonstrated that these projectors have a negligible to low risk associated for exposure within 1 meter, then projectors with lower emission levels and shorter hazard distances also have a negligible associated risk.

The risk analysis is based on two main parameters:

- the diameter of the pupil of the eye, and
- the safety margin inherent in the AEL for the case of image projectors, where the wavelength distribution and apparent source size is well defined for the type of projectors that are to be discussed.

In the analysis, for all relevant parameters, conservative to worst-case scenarios are chosen in order to have a robust risk analysis. The employed sequence of analysis is: first, it will be analyzed by how much the exposure limit can be exceeded for short distances considering a 7 mm pupil when the exposure level is equal to the limit for 1 meter distance. Secondly, biophysical data will be discussed that support the conclusion that at short distances, the pupil can be assumed to be smaller, taking into account image projector specific properties such as soft-start and that even for “black” images there is still substantial light emission present. Smaller pupils correspondingly reduce the factors by how much the exposure limit is exceeded. Thirdly, for the relevant apparent source sizes and wavelength distributions, predicted injury threshold values will be compared against exposure levels (rather than comparing exposure limits with exposure levels).

Basic Comparison with Exposure Limit

This analysis is based on the worst-case where the AE is just below (in effect equal to) the AEL of RG2 at a distance of 1 meter. The reference point for the classification distance of 1 meter is the outer surface of the outer projection lens. Specifically, the effective radiance is equal to the exposure limit (EL) for retinal thermal injury for 0.25 s since the EL value is equal to the respective AEL for RG2. Since the analysis is considering exposures at shorter distance than 1 meter, it is based on EL and not on AEL values. The exposure limit equals [ICNIRP, CDV]

$EL = \frac{28000}{\alpha} \frac{W}{m^2 \cdot sr}$ where α is in units of rad and is the angular subtense of the apparent source. For image projectors the relevant apparent source is the exit pupil of the projection lens system [3] and can be understood as the beam waist.

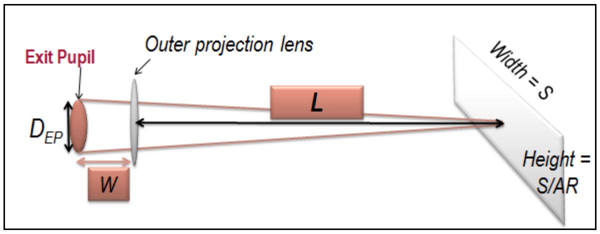

Fig. 1. Simplified drawing of the relevant parameters; the projector beam width and height is indicated on the right, the exit pupil is within the projection lens (which is not shown).

The exit pupil is some distance W within the outer surface of the outer projection lens, and when L is the symbol for the distance to the projection lens, and D_{EP} is the diameter of the exit pupil, then for a top hat profile of the exit pupil

$$\alpha = \frac{D_{EP}}{L+W}$$

If there are no substructures in the profile of the exit pupil, then radiance, as exposure level, can be calculated by dividing the total beam power by the area of the beam at distance L (to obtain the irradiance in the beam) and further division by the solid angle that is subtended by the exit pupil as seen from distance L. It can be easily shown that this quantity, as is generally the case for radiance (as long as there are no averaging effects based on substructures within the averaging field of view) does not depend on distance (see also for instance [5]). What *does* depend on distance is the angular subtense of the apparent source and therefore the EL, since the EL depends inversely on source size; the angular subtense of the apparent source increases by the same factor that the distance L+W decreases. Thus, if at the distance of L+W the exposure is equal to the exposure limit and that distance is halved, the angular subtense of the apparent source is doubled and the EL is halved, so that for that distance, for the scenario investigated here, the *EL* is exceeded by a factor 2. It should be noted that the impact of varying the distance to the projector *L* regarding how much the *EL* is exceeded is dampened by the distance W (halving *L* does not decrease the *EL* by a factor of 2). In terms of a conservative assumption, rather small values of *W* should be used, and a conservative value of 10 cm is chosen here (again it should be noted that the type of project under discussion is in the higher luminance category of at least 10 000 lm, which also has a correspondingly large projection lens system). In reality the position of the exit pupil and radiance relates to multiple parameters:

- imager size
- optical power emitted through the projection lens
- f/# number of the projection lens
- throw ratio settings

With $W = 0.1$ m the EL is exceeded by a factor of 1.9 for $L = 0.5$ m, by a factor of 3.7 for $L = 0.2$ m and by a factor of 5.5 for a distance to the lens of 10 cm. These values do not depend on the angular subtense of the source as long it is not larger than 100 mrad, which for the projectors and projection optics at hand is the case: in terms of hazard distance, a large throw ratio TR is more conservative, and a value of TR = 2 is assumed, which means that the ratio of distance to the screen over the screen width is 2, i.e. for 10 meter distance to the screen, the image has a width of 5 meters; for a TR = 4, at 10 meters the screen width (or actually image width) equals 2.5 m. The throw ratio can also be understood as 1 over the divergence of the beam (in radian) in horizontal direction, i.e. long throw ratio means small divergence. The TR = 2 is specified in IEC 62471-5 as test condition in case the projector can be equipped with a interchangeable lens, this is specific classification throw ratio is conservative for the majority of installations. In addition it makes comparison between two types of projectors possible. A larger throw ratio for the same light output (lumen) produces a wider hazard distance as the exit pupil increases and the EL decreases. Due to the limited space, projectors intended for home cinema or data projectors for meeting rooms typically have a throw ratio that is not larger than 2. For projectors for common consumer market or meeting rooms, the lens is fixed and cannot be interchanged, but has a zoom range. In this case, the test requirement is such that the classification has to be performed at the worst-case setting of the zoom. The diameter of exit pupils will be discussed in more detail further below, but here it is noted that for a TR of 2, the exit pupil diameter is conservatively assumed to be not larger than 18 mm (as smaller exit pupils will be shown to have smaller safety margins), so that with $W = 0.1$ and $L = 0.1$ m from the optics, the angular subtense of the apparent source a equals 90 mrad.

Eye Pupil Diameter

In the previous section it was derived that the EL can be exceeded by a factor of 3.7 for exposure 20 cm from the projection optics, and as an extreme value of 10 cm from the optics, by a factor of 5.5. These values apply to the assumption that the pupil of the eye has a diameter of 7 mm, which is the basis of the definition of the EL for exposure durations up to and including 0.25 s. The diameter of the pupil for the case that exposure occurs at close distance to the projector is both an important factor as well as a factor that has a considerable variability and uncertainty. For instance, if the pupil diameter when exposure occurs is 3.5 mm rather than 7 mm, only ¼ of the light enters the eye, which means that while the EL is exceeded by a factor of 3.7 at 20 cm distance from the projector when the pupil has a diameter of 7 mm, the EL is *not* exceeded when the pupil diameter is 3.5 mm.

The pupil diameter is influenced by many parameters and is not simply a function of light level, for instance. There is general agreement in the relevant literature that for the same experimental conditions, there is a very large individual variability of the pupil diameter in the range of a factor of 2 spread (see references in [10]).

It also needs to be considered what kind of exposure scenarios can lead to an exposure in the first place, and particularly with a rather large pupil. The scenario that it is dark or very dimly lit, the projector is switched off and the person happens to be in the path of the beam and looks into the projector from a distance less than 1 meter and then the projector is switched on, appears as relatively rare considering that these higher power projectors are mounted on the ceiling or in projection booth – but is not impossible. However, for this scenario, it is relevant to note that IEC 62471-5 for RG2 and RG3 projectors requires (FDIS status, Clause 6.3) that there is a “soft-start”, i.e. the full emission level after the projector has been switched on is only permitted to be reached after 1 second. Due to the soft-start, there is sufficient time for aversion response to bright light, i.e. reduction of the pupil diameter to take effect. A second scenario is that the projector is active but a black image is projected, which is then switched to white at the position and time where a person is at close distance and looking into the projector. For this scenario it is relevant that “black” does not mean there is no light coming out of the lens but there is related to the contrast ratio of the projector. Typically this is a significant amount of light leakage (see Fig. 2), which actually appears very bright for a 10 000 lm projector when intrabeam exposure occurs and the pupil would constrict within a short period of time once the person has the projector in the field of view, even when the projection is set to “black”.

Fig. 2. As example, a >10 000 lm projector, for the photo on the left switched to black state, while for the photo on the right the image is full white, both viewed from outside of the beam. The lower photo shows intra beam viewing during the black state.

Another issue that is relevant is that for a position outside of the beam, there is stray light to be seen that exits the projection lens, so that this should also prompt a person to be aware of the projector and beam. The amount of stray light relates to the optical output of the device.

Regarding a pupil diameter of 7 mm, this is sometimes portrayed as only applicable for dark adapted pupils, implying that if there is some lighting, the pupil will surely be smaller. However, for a conservative analysis this assumption is not correct, and there are many individuals, particularly younger people, who have 7 mm pupils also at moderate light levels, and apparently also have reasonable visual acuity (i.e. the aberrations of the eye for larger pupils are for these individuals apparently not great) [11]. This again demonstrates the large individual variability, as studies by Campbell 1966 and Donnely 2003 showed that the optimum pupil size for high acuity vision is about 3 mm [12, 13].

What is highly relevant for this analysis is that at close distances, when the eye accommodates to image a close-by object, the “near triad of accommodation” (see for instance [14]) means that not only lens power changes to optically image the near-by target (what is generally called accommodation), but also the axis of eyes center on the target (convergence) and, important for this discussion, there is pupil constriction (miosis) (Fig. 3).

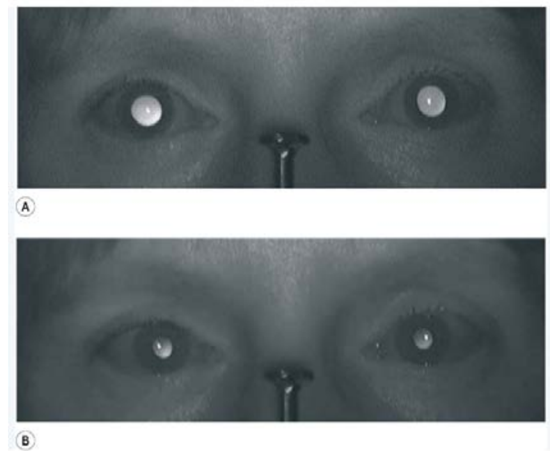

Fig. 3. Infrared photo showing pupil constriction and convergence as the subject changes fixation from **A,** a distant object to **B,** a near object. From [15].

If there is no accommodation (the lens thickness is not adjusted to image the target sharply, in this case the exit pupil), then the retinal image would be larger and/or blurred and the retinal irradiance would be reduced. The near triad of accommodation is a reflex, i.e. pupil constriction in association with lens accommodation and convergence is controlled by the Edinger-Westphal nucleus in the mid-brain.

It should be noted, however, that the response apparently also has some individual variability, as data from the literature is not fully consistent. The result of one study is shown in Fig. 4. where the open circles are pupil diameters plotted aver the stimulus in diopter, where 5 Diopter means a distance of 1 m/5 = 20 cm, for which pupil diameters are between 4 to 5 mm [16].

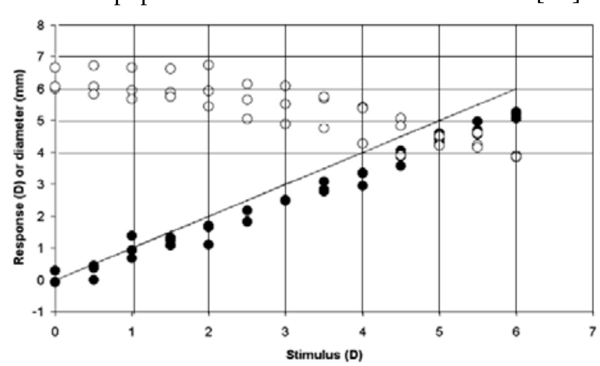

Fig. 4. Example of the accommodation and pupil data from three runs with one emmetropic subject. Filled symbols represent accommodative response and open symbols represent pupil diameter (adapted from [16]).

Oyster [17] reported that when the eye accommodated to a point of about 1 m in front of the eye or closer, the pupil diameter becomes smaller (the pupil constricts) the closer that point gets; for a distance of 1 m, pupil diameters between 3,5 mm and 4,5 mm are given. Kasthurrangan [18] reports that the reduction is that pronounced only for a young eye, for an observer with 40 years of age, the pupil diameter was 6 mm for accommodation to a lit object 6 m away presented in a dark room and decreased by 1 mm (i.e. to 5 mm) for accommodation to 30 cm (3 Dioptres). In one study, however [19] it was noted that in some cases there was adoption to a close target but the pupil remained at a relatively large diameter of 7.5 mm. In a later study, however, Gislen et al. [20], reported a relatively strong effect both for adults and children for low light levels of 5 lux, where the pupil for no accommodation was about 6.5 mm in the average and less effect for 100 lx light level, where, however, the pupil size was between 4 to 5 mm for no accommodation.

Considering not only the near triad of accommodation but also that the critical distance to the projector is in order of 20 cm to 50 cm and there is a required soft-start as well as that there very bright emission even when the image is "black", it should be possible to assume for a risk analysis considering "normal worst-case" scenarios that the pupil at half a meter distance from the projector is not larger than 5 mm and at 20 cm from the projector is not larger than 4 mm.

For a critical risk analysis, as an extreme worst case, it should also be noted that there are some medical conditions that are associated with larger pupils also under illumination, as well as that pupils are intentionally dilated for eye exams and accidental dilation sometimes occurs for nurses handling drugs that are used to dilate pupils, see for instance [10].

Consequently, two sets of pupil diameters are proposed to be used: one for a typical but still conservative analysis with 7 mm pupil at 1 meters distance that decreases to 4 mm at 10 cm distance. It is noted that accommodation onto the exit pupil and low spherical aberration is needed in order to achieve the assumed retinal irradiance levels, and a combination if these can be considered as not reasonably foreseeable for normally reacting pupils at close distances considering the above issues of soft-start and high brightness when looking into the projector even for black images. For the case of medical conditions and drugs that prevent constriction of the pupils, an additional analysis will be carried out for generally large pupils.

Projector Parameters

As will be shown, the margin between EL and injury threshold varies in a significant way as a function of retinal image size (i.e. angular subtense of the apparent source). The safety margin is largest for large retinal images. Therefore, in terms of a "cautious" risk analysis that is based on conservative assumptions, it is necessary to determine the *smallest* exit pupil that is associated with projectors that have a hazard distance of 1 meter.

The diameter of the exit pupil is directly related to the size of the imager chip, which is the device which in terms of pixels is imaged onto the screen and is either a DMD (digital micromirror device) or LCoS (liquid crystal on silicon). Devices with very high luminous power require one image chip for each colour (i.e. three chips) typically with a diagonal of 0.96" or larger, the maximum luminous power of such devices, due to thermal load and optical restrictions being about 30 000 lm. Currently the largest chip size is 1.38" and luminous power levels of up to theoretically 80 000 lm. From the cost, these three-chip systems can be considered professional cinema projectors. Devices with the somewhat smaller (but still relatively high end) chip of 0.67" diagonal is typical for devices where one chip is used for all colours, so that a colour wheel is needed to consecutively produce the images for the respective colours. Due to the thermal load and optical restraints, the maximum luminous power of such devices is limited to about 15 000 lm. This is just in the range where it cannot be excluded that a HD of 1 meter is possible. For the next smaller chip, 0.45", the maximum luminous power is about 7500 lm which no longer has a hazard distance range that is of relevance in this discussion. Thus the smallest chip size to consider here is 0.67". The relationship between the throw ratio TR, the f/# of the optics (taken as 2.0 for 0,67" and 2.5 for 0,98") and the chip diagonal is:

$$D_{EP} = \frac{TR \cdot Chip\_Size}{f\,/\,\#}$$

The values as reported from industry are plotted as function of throw ratio for the two relevant chip sizes in Fig. 5.

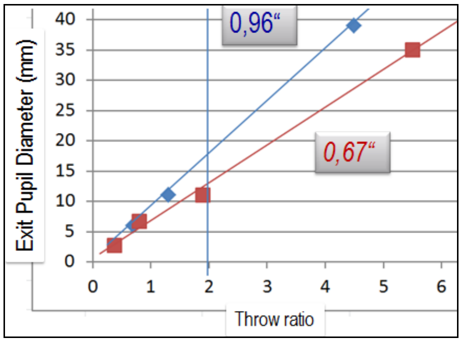

Fig. 5. Exit pupil diameter for two chip sizes of 0.96" and 0.67" as function of throw ratio (the ratio of distance to screen to width of screen).

For a TR=2, the exit pupil equals about 12 mm for the smaller chip and about 18 mm for the 0.96” chip. For higher lumen systems, which are the potentially critical devices in this discussion, there is also a reasonable minimal screen size as otherwise the image would be too bright to be comfortable to watch. It follows that for systems to be used in a home cinema (although that would be an extremely high-end home cinema) or meeting room with smaller spacing as in a conference hall or in a cinema, the throw ratio of the optics would be around TR=2 with a range of 1.5 to 3. In terms of models that have hazard distances of 1 meter and not less, these would typically have the larger chip size of 0.96”, with a larger exit pupil. In the analysis below, an exit pupil of 12 mm is chosen as conservative assumption applicable to a TR=2 for the small chip size, which for the larger chip size of 0.96” in above figure is the exit pupil diameter that applies for or a TR=1.3 .

Injury Model

The Seibersdorf Laboratories Injury Model was used to predict retinal thermal injury and is described in detail in [21, 22]. It is note here that it is validated against all applicable experimental injury threshold data obtained with non-human primates (mostly rhesus monkeys). The computer model was adjusted to the properties of the human eye as follows:

- the size of a threshold lesion to the retinal pigment epithelium (in the sense of a minimum visible lesion) was reduced from 50 µm to 20 µm because it cannot be ruled out that such small lesions are vision impairing when located in the central portion of the retina (fovea) although such small lesions are not detected by ophthalmoscopic means [23].
- the minimum retinal spot size was set to 25 µm; see discussion in [24]
- the air equivalent focal length of the relaxed human eye was set to 16.68 mm (see Le Grand full theoretical relaxed eye in [25])

According to this model, the resulting injury threshold for a given wavelength, irradiance profile and exposure duration is a prediction of the experimental ED_{50} level, i.e. the total intraocular energy required to induce a minimum visible lesion to the retina with a probability of 50 % [7]. It is emphasised that the predictions are still based on data obtained with non-human primates and the above adjustments do not relate to the actual injury threshold; i.e. it is noted for instance in [8] that the injury threshold for humans, where available, was consistently higher than for the non-human primates; a factor of 2 for regions outside of the macula and a factor of at least 1.3 for the macular region for the case of a broadband white light source with an retinal image diameter of 1 mm. However, it is noted that direct comparisons of thresholds from human volunteers with non-human primate experiments is very scarce.

When taking the set of data applicable for the macula (lowest thresholds due to highest pigmentation) and exposure durations less than 10 seconds, the maximum deviation of the computer model compared to non-human primate data is 1.3 w.r.t. to predicting an injury threshold that is higher than the experimental value for the same wavelength, exposure duration and retinal spot size. This value of 1.3 has to be applied as a minimum factor to scale the model to the lower edge of experimentally found ED50 values. Additionally, a factor needs to be applied to scale the 50% thresholds to a value where the probability of injury is in a range which can be referred to as negligible. Based on a rather steep dose response curve, this reduction should be of the order of 1.3, which would result in an overall reduction of the predicted injury thresholds by 1.7. This also fits with the observed minimum factor between the model predictions and exposure limits for top hat retinal irradiance profiles which for 530 nm (the wavelength with the lowest injury thresholds) equals a factor of 1.5 for 3 mrad angular subtense and 5 ms exposure duration and shows that the model is rather on the conservative side. To be on the conservative side, instead of an overall reduction of 1.7, the model data was reduced by a factor of 2, so that there is a good argument to classify the resulting level as “safe”, i.e. negligible risk for injury, or HSE, for “highest safe level”. It should be noted that there is still a significant uncertainty involved when it comes to predict the risk for injury for humans, as the above data is applicable for non-human primates which so far, whenever a comparative study was performed with human, exhibited lower injury thresholds even for highly pigmented humans (see the review by Bruce Stuck [8]).

The EL and HSE for 530 nm and 250 ms exposure duration is shown in Fig. 6.

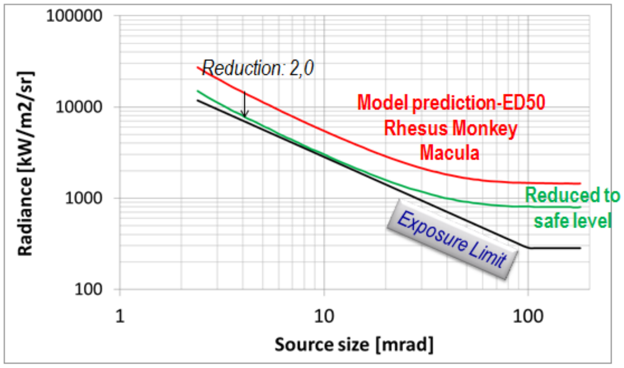

Fig. 6. Exposure limit and model predictions as function of source (retinal image) size, for 250 ms exposure duration and 530 nm wavelength.

The ratio of HSE over EL (data of Fig. 6.) is plotted in Fig. 7.:

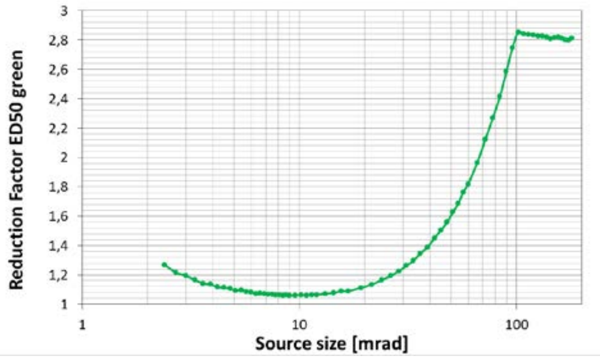

Fig. 7. Ratio of HSE over EL for 250 ms exposure duration and green wavelength.

The variation of this reduction factor (or safety margin) with source size is considerable: it is minimum (close to 1) at 10 mrad, but increases up to 2.8 for 100 mrad. It follows that the safety margin increases for closer distances to the projector.

The injury thresholds were calculated for typical wavelength distributions for xenon lamps and laser illuminated projectors, and as expected, the injury threshold is higher as compared to 530 nm. As a worst case smallest difference, the conservative value of 1.1 ratio between the projector spectrum and 530 nm is used.

Discussion

The data presented in the above sections can now be combined to produce a table where the different aspects are accounted for (Table 1), for the conservative assumption of an exit pupil of 12 mm, recessed by 10 cm from the front surface of the projection optics.

Table 1. Results for assumptions for typical worst-case pupil diameters.

Dist. to lens	Dist. to Exit Pupil	Angular subt. of app. source	Factor above EL for 7 mm pupil	Pupil diam.	Area Pupil factor	Factor above EL for pupil	min. Safety margin	Risk factor
1	2	3	4	5	6	7	8	9
L	L+W	α						
m	m	mrad		mm				
1,0	*1,1*	*11*	*1,0*	*7*	*1,0*	*1,00*	*1,11*	*0,90*
0,9	1,0	12	1,1	7	1,0	1,10	1,11	1,00
0,8	0,9	13	1,2	6,5	1,2	1,05	1,12	0,94
0,7	0,8	15	1,4	6	1,4	1,01	1,13	0,90
0,6	0,7	17	1,6	5,5	1,6	0,97	1,14	0,85
0,5	0,6	20	1,8	5	2,0	0,94	1,16	0,80
0,4	0,5	24	2,2	5	2,0	1,12	1,21	0,93
0,3	0,4	30	2,8	4,5	2,4	1,14	1,30	0,87
0,2	0,3	40	3,7	4	3,1	1,20	1,46	0,82
0,1	0,2	60	5,5	4	3,1	1,80	1,89	0,95

The columns are numbered so that they can be discussed here:

Column 1 is the distance to the front surface of the projection lens; the first line in the table is for the disance *L*=1 meter

Column 2 is the distance to the exit pupil

Column 3 is the angular subtense of the apparent source, i.e. 12 mm/(*L*+*W*)

Column 4 is the factor by which the EL, for a pupil of 7 mm diameter is exceeded (this is the factor by which α is getting larger for shorter distances)

Column 5 is the assumed pupil diameter where the pupil diameter of 7 mm is maintained also for 90 cm, 5 mm is used for 50 and 40 cm, and for 20 cm and 10 cm, 4 mm is used. Note that these are not certain values but are to be understood as defendable conservative values considering the emission features such as soft-start and that the emission is also very bright for “black image” and that stray light in the projection lens can also be seen outside of the beam.

Column 6 is the factor by which the pupil area is smaller as compared to the 7 mm pupil

Column 7 is the factor by which the EL is exceeded when the pupil diameter of column 5 is used (i.e. Column 4 reduced by Column 6)

Column 8 is the minimum safety margin shown in Fig. 7 but increased by a factor 1.1 to account for the full spectral white emission.

Column 9 is the result of applying the safety margin of Column 8 to the values of Column 7; it is noted again that the predicted injury thresholds (that are based on non-human primate data) were reduced by a factor of 2 which is on the safe side (a factor of 1.7 could also be argued as to be sufficient) and that the biggest uncertainty here is the difference of the non-human primate’s threshold to the threshold of the human retina. It can be seen that for all distances, this figure of merit is equal to 1 or less than 1, which is a good basis to characterise exposure under typical worst case conditions (but not absolute worst-case conditions) as negligible risk, where “negligible” is the term used in risk analysis for a risk which is close to “zero”, but the term zero risk is avoided in risk analysis out of general principle.

Finally, the absolute worst-case scenario of a dilated pupil that does not react to light stimulus is considered. The results are shown in Table 2. A value of 8 is used here even for very short exposure distances. This scenario is possible for medically dilated pupils which do not constrict upon exposure to light, and it is also assumed that there is no relevant spherical nor chromatic abberations which would lead to increased image size, which for such large pupils is rare.

Table 2. Results for assumptions for absolute worst-case medically dilated pupil diameters.

Dist. to lens	Dist. to Exit Pupil	Angular subt. of app. source	Factor above EL for 7 mm pupil	Pupil diam.	Area Pupil factor	Factor above EL for pupil	min. Safety margin	Risk factor
L	L+W	α						
m	m	mrad		mm				
1,0	*1,1*	*11*	*1,0*	*8*	*0,8*	*1,31*	*1,11*	*1,18*
0,9	1,0	12	1,1	8	0,8	1,44	1,11	1,30
0,8	0,9	13	1,2	8	0,8	1,60	1,12	1,43
0,7	0,8	15	1,4	8	0,8	1,80	1,13	1,59
0,6	0,7	17	1,6	8	0,8	2,05	1,14	1,81
0,5	0,6	20	1,8	8	0,8	2,39	1,16	2,06
0,4	0,5	24	2,2	8	0,8	2,87	1,21	2,37
0,3	0,4	30	2,8	8	0,8	3,59	1,30	2,76
0,2	0,3	40	3,7	8	0,8	4,79	1,46	3,27
0,1	0,2	60	5,5	8	0,8	7,18	1,89	3,79

Up to a distance of 50 cm, the risk factor is less then 2, and since the difference between injury thresholds of human retinas and non-human primates is also characterised to in that range, the risk for injury for these distances can still be said to be relatively low, which is usually acceptable in terms of product safety. For distances less than 50 cm, the risk factor is larger than 2, up to almost 4 for 10 cm. Here it should be considered that besides of the generally very short distance and the relatively low probability that a person is exposed within this short distance, in addition these are relatively large projectors usually mounted on the ceiling or in a restriced projection booth. As discussed previously there will always be light leakage present and a soft-start is a required safety featureIt is important that besides pupil constriction there are also other aversion responses to bright light such as squinting and looking away, which reduces the exposure and therefore the risk even if the pupil does not constrict. For an exposure with dilated pupils as a medical conditions or from drugs to occur within 50 cm from a higher power projector, in combination with good visual acuity and accomodation to the exit pupil can as such be considered as very low probabiltiy and together with the other aversion responses to bright light, a potentially critical expsoure could almost be considered as interntionally looking into the bright light. This is (excluding child appealing products) considered accepable at least by European market surveillance authorities [26], i.e. if there is a risk for injury when a person intentionally stares into the bright light is considered acceptable as long as the risk for injury from momentary exposure (unintentional exposure) is low.

Thus the risk for these absolute worst case scenarios is not “zero”, i.e. not negligble, but should still be considered as acceptable, considering

- other aversion responses to bright light such as squinting and turning away,
- the low probability for an expsoure to occur with this scenario, as well as
- human behavioral safety
- that the analysis is based on injury thresholds of non-human primates and the injruy thresholds of humans, where directly compared, were consistently higher than for non-human primates.

Summary

IEC 62471-5 defines the criteria for determining risk groups for image projectors. Risk Group 2 (RG2) is understood to be safe also as consumer product. The reference distance for determination of the risk group is defined as 1 meter from the projector lens. This means that for RG2 projectors, the retinal thermal exposure limit for accidental exposure can be exceeded for exposure distances less than 1 meter. For the worst case assumption the exposure at 1 meter equals the exposure limit, a risk analysis was performed to discuss the risk for injury related to exposure very close to the projector. The analysis is mainly based on estimating reasonably foreseeable pupil diameters and on safety margins inherent in the exposure limits. For the choice of the pupil diameter it is important to note that a soft-start of the projector is required, and once the projector is active, that even for a “black” image there is considerable light emission. For pupil diameters that can be said to be conservative but not absolute worst-case, the exposure can be shown to be below conservatively predicted injury thresholds. The absolute worst-case represents a fully dilated pupil that is non-responsive due to medical conditions or medication. For very close exposure distances of the order of less than 50 cm or less, looking into the projector and imaging the exit pupil, i.e. when other aversion responses are suppressed, retinal thermal injury cannot be excluded for high power RG2 projectors (which, however, are usually mounted on the ceiling or in projection booths). Considering the very low probability for all of these worst-case scenarios to occur at the same time, the risk can be characterized as low enough in terms of overall expected level of safety for consumer products that emit bright light. An important aspect is here that a product that emits bright light is not required to be absolutely risk-free, particularly when aversion responses are intentionally suppressed.

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worldwide projector manufacturers and their customers and suppliers. More information about LIPA is available at www.LIPAInfo.org.

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Meet the Authors

Karl Schulmeister, PhD, is a consultant on laser and broadband radiation safety at the Seibersdorf Laboratories, where also a specialized accredited test house is operated. He is member of IEC TC 76 and liaison between IEC and ICNIRP. In 1999, his group developed a fully probabilistic risk analysis model for space based lasers for the European Space Agency based on injury threshold data from the literature, and since then one of the main interests is risk analysis for laser product safety. The research in his group over the last 10 years concentrated on thermally induced injury, leading to the development of a computer model that was validated for quantitative analysis of the risk for injury for a wide range of wavelengths and pulse durations.

Jan Daem is an Optical radiation safety expert and product safety engineer at BARCO and Chairman of the European Regulatory Sub-Committee & Finance Committee, Laser Illuminated Projector Association (LIPA). Jan Daem is currently focused solely on the worldwide introduction of laser illuminated projector systems. In this position as well as Chairman of the European Regulatory Sub-Committee, he is ensuring safety standards and regulations are created without unnecessarily-strict restrictions upon manufacturers and without undue safety hazards for consumers and AV professionals. The activities include managing a worldwide team of professionals evaluating the light emitted from projectors, as well as interacting with regulatory officials at region, state and EU Commission levels. Jan is also very active on the IEC TC-76 Committees.