Paradigm Change for Optical Radiation – Temporary Blinding from Optical Radiation as Part of the Risk Assessment

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Abstract. According to the European Directive 2006/25/EC on artificial optical radiation the employer has to determine the exposure and to perform a risk assessment. Up to now only deterministic risks are treated in such a risk assessment concerning optical radiation. Although the European Directive on artificial optical radiation 2006/25/EC states that indirect effects from e. g. temporary blinding shall be included in the risk assessment only sparse quantitative data are thus far available.

As a result of a research project quantitative relationships have been determined in order to be applied for laser radiation and high-brightness light emitting diodes of various colours, respectively. A logarithmic dependence of the duration of impairment of several visual functions, like visual acuity, especially the capability to read, as a function of the applied optical energy has been experimentally found. In addition threshold values are derived from experimental results. Last not least a proposal to classify artificial sources of visible optical radiation based on the capability to impair vision temporarily is presented.

Keywords: Temporary blinding, risk assessment, laser radiation, high-brightness LEDs, visual acuity

1. Introduction

Within the meaning of the so-called Framework Directive 89/391/EEC [1] the European Parliament and the Council have published the 19th individual Directive 2006/25/EC [2]. This directive on artificial optical radiation addresses non-coherent radiation and laser radiation together. It lays down the minimum health and safety requirements for protection of workers from risks arising from exposure to optical radiation from artificial sources. According to this directive the employer has to determine the exposure at the workplace and the respective values have to be below the specified exposure limit values (ELVs), which are based on various ICNIRP (International Commission on Non-Ionizing Radiation) guidelines. In addition, he shall give particular attention to any indirect effects amongst others such as temporary blinding, when carrying out the risk assessment.

Up to now, hazards arising from optical radiation are dealt with almost exclusively taking into account only deterministic damages with a clear threshold and a swelling behaviour. Neither stochastic nor indirect effects are treated in the respective safety standards.

Since modern light sources like laser and high-brightness light emitting diodes (HB-LEDs) gain increasingly more applications not only harmful radiation might become accessible at work and for the general public, but in addition temporary blinding from these bright light sources might cause indirect effects, which may have general safety implications. Up to now secondary effects like temporary blinding have not been regarded in safety standards and there exist but a few data on this topic as far as modern artificial high intensity light sources are concerned.

It is well-known that people are able to adapt under normal illumination conditions to changing luminous levels. But even with sub-threshold exposure glare might impair visual functions more or less, especially due to a dazzling effect of a bright light source in the field of view or due to the after-image formation, which is mainly the result of photochemical changes in the respective photoreceptors, i. e. cones and rods, and in addition some neural influence from the visual cortex might contribute to the after-effect. During the refractory time an exposed individual is visually handicapped. This might result in serious incidents or even accidents.

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In order to get more reliable quantitative data concerning the influence of glare, dazzle, flash-blindness and afterimages it was the goal to investigate the various parameters which mainly determine the respective impact on vision. Therefore low power laser and various HB-LEDs have been applied in specially designed and computer assisted test setups in order to determine the duration of disturbance of visual acuity as well as the impairment to read as a function of the applied wavelength, optical power and exposure duration.

Employers should especially make adjustments in the light of technical progress and scientific knowledge regarding risks related to exposure to optical radiation, with a view to improving the safety and health protection of workers.

Due to the fact that the accessible emission limits (AEL) of class 1 laser products and the maximum permissible exposure (MPE) values have been increased it is mentioned now in the 2nd edition of the international laser safety standard IEC 60825-1 [3] in the description of this laser class that intrabeam viewing may produce dazzling visual effects, particularly in low ambient light, if the radiation is in the visible part of the spectrum. This is the first time that such effects are mentioned in this standard and for class 2 and 2M laser products the standard states in this case that indirect general safety implications might result from temporary disturbance of vision or from startle reactions.

2. Methods

Recent research has shown that there exist functional connections between the exposure parameters and the subsequent impairment of visual functions, especially due to the appearance of after-images [4, 5], but there are still open questions. Therefore the main objectives were to determine the time duration after which visual acuity returns to its previous value after temporary blinding from a laser beam or an LED.

In a first study a well-collimated helium-neon laser beam ($\lambda = 632.8$ nm) was used in order to irradiate the fovea in the retina. The laser power was adjusted in order to investigate the respective dependence of the afterimage well below the AELs of class 1 according to IEC 60825-1 [3]. Due to the fact that volunteers perceived a higher optical power as psychologically uncomfortable the applied power was restricted to an upper limit of 30 µW. A detailed description of the measurement setup is given elsewhere [6]. Measurements of the afterimage duration have been done for exposure durations of 1 s, 5 s, and 10 s at 5 µW, 10 µW, 20 µW, and 30 µW, respectively.

The investigations were relatively time consuming due to the fact that sufficient re-adaptation time was necessary after each exposure in order not to falsify the results due to an interfering residual afterimage. The trials have been done with a total of 10 volunteers in the laboratory. The moment when the afterimage disappeared and could not be retrieved not even by squinting was taken as stop criterion for the determination of the duration of the afterimage.

In a second much more elaborate study various optical sources were chosen as stimulating bright lights, i. e. lasers with wavelengths of 632.8 nm and 532 nm and coloured high-brightness LEDs (HB-LEDs), namely red, green, royal blue and white. The maximum optical power in a 7-mm aperture, which is equivalent to the pupil diameter of a dark adapted eye, was 0.783 mW in the case of a laser, i. e. about 20 % below the maximum accessible emission limit of class 2 according to IEC 60825-1, and 3 mW for the LEDs. The exposure duration was chosen to be 0.25 s, 0.5 s, 1 s, 5 s, and 10 s in the case of laser irradiation and 0.25 s, 1 s, 5 s, and 10 s for LEDs.

As a method to determine the recovery time after an irradiation with a laser beam a special computer assisted reading test has been developed, where word creations for similar words which differed in one single character are presented on a monitor and the recovery time has been determined when the subject was able to read them correctly. On the other hand a modified commercially available binoptometer with Landolt-C rings as optotypes was used to determine the recovery time after an irradiation with an LED. In both cases the after-image and its persistence were responsible for the delay in the ability to read after an irradiation. Altogether 19 subjects have been irradiated with a laser beam and 26 with an LED in these particular investigations. The respective test conditions are summarized in table 1.

Table 1. Test conditions in the recovery acuity duration tests

Source	Parameters		Number of trials	Sum of trials
LASER	Wavelength/nm	632.8	943	1,267
		532	324	
	Exposure duration/s	0.25, 1, 5, and 10		
	Maximum optical power/mW	0.783		
LED	Colour (Wavelength/nm)	Red (640)	735	2,824
		Green (520)	821	
		Royal blue (460)	640	
		White	628	
	Exposure duration/s	0.25, 1, 5, and 10		
	Maximum optical power/mW	3		

Table 1 shows that a total of 4,091 irradiations have been performed with 26 different conditions. The various test procedures and measurement methods have been described elsewhere in more detail [7].

All participants have been provided with the essential information concerning the aim of the investigations and gave their written consent to take part in the respective trial. Since the internationally agreed exposure limit values were never exceeded as far as the particularly adjusted exposure values concerns, there was never a real existing risk of an adverse effect to the eyes of the subjects.

3. Results

Afterimage durations up to 300 seconds were found if the fovea of the human retina was irradiated from a class 1 laser beam with an optical power less than 10 percent of the AEL, which is 390 µW in the wavelength range between 500 nm and 700 nm according to IEC 60825-1.

A dose-relationship was found concerning the duration of an afterimage as a function of exposure duration in the time interval between 0.25 s and 10 s. This functional interrelationship between the applied optical energy and the respective afterimage duration in the case of a helium-neon beam is displayed in figure 1.

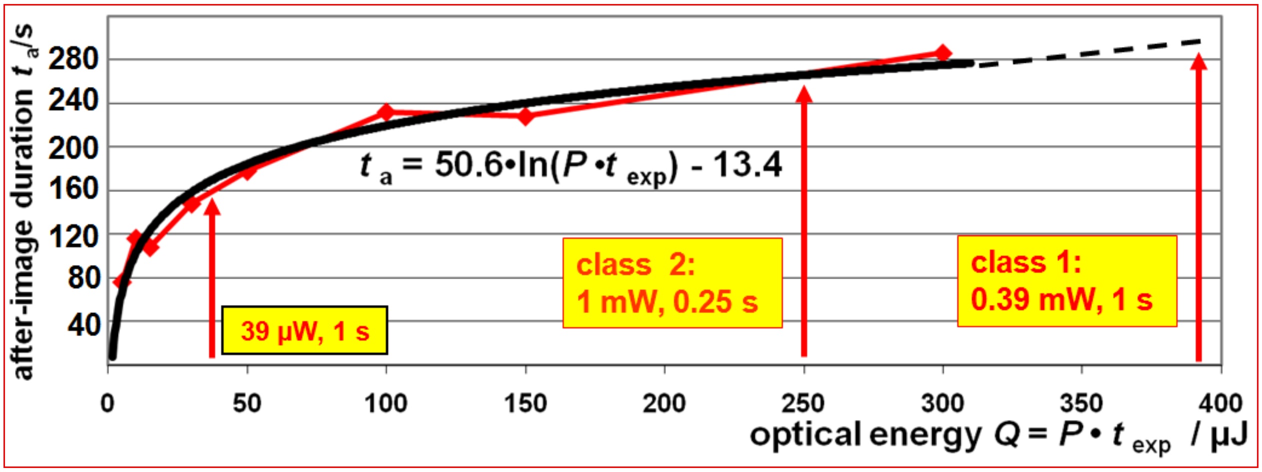

Figure 1. After-image duration t_a as a function of optical energy $Q = P \cdot t_{exp}$ ($\lambda = 632.8$ nm); red diamonds represent mean values of measurements; thick black solid line: expected interrelationship, dashed line: expected extension of the afterimage duration above 300 µJ; red arrows for comparison: class 2 laser (upper limit 1 mW, 0.25 s), class 1 laser (examples with 39 µW, 0.39 mW and an exposure duration of 1 s)

The after-image duration t_a in seconds produced by a red laser beam ($\lambda = 632.8$ nm) was determined to be:

$$t_a/\mathrm{s} \approx 50.6 \cdot \ln[(P \cdot t_{exp})/\mu\mathrm{J}] - 13.4, \qquad (1)$$

for laser output powers P between 5 µW and 30 µW with exposure durations t_{exp} from 1 s up to 10 s, if the beam hits the fovea. It might be seen that there exists a saturation behaviour in this curve. In addition it is possible to derive theoretical threshold values for the exposure duration $t_{exp,th}$ from eq. (1). This is shown in eq. (2).

$$\boxed{\frac{t_{exp}}{s} = \frac{e^{\frac{13.4}{50.6}}}{\frac{P}{\mu W}} \approx \frac{1.303}{\frac{P}{\mu W}}} \Rightarrow \qquad (2)$$

From $t_{af,fovea} \approx 50.6 \cdot \ln[(P \cdot t_{exp})/\mu J] - 13.4 = 0$ the threshold value for the exposure duration is achieved
$t_{exp,th} = 1.3$ s for 1 µW or $t_{exp,th} = 0.13$ s for 10 µW or
$t_{exp,th} = 13$ ms for 100 µW or $t_{exp,th} = 1.3$ ms for 1 mW

In the investigation it has been found that the after-image duration strongly depends on the location of the laser beam spot on the retina. For example, if the irradiation is at an angle 5 degrees nasally or temporally of the foveal pit, the respective after-image duration decreases to about 50 percent compared to the maximum in the fovea. More detailed results can be found in [6].

The measured time delay or impairment time was not simply the after-image duration (recovery time) but connected with either the visual acuity or the reading capability, which is achieved after about 10 % to 30 % of the total afterimage duration. An after-image duration of 200 s to 300 s is equivalent to a reading inability duration between 20 s and 90 s.

The visual acuity recovery time t_{VA} for a green HB-LED (λ = 530 nm) has been found to obey the following dose relationship between t_{VA} and the optical energy Q:

$$t_{VA}\,/\mathrm{s} \approx 3.7 \cdot \ln[Q/\mu J] - 16.2, \qquad (3)$$

e. g. in the power range 0.12 mW to 1.5 mW and for exposure durations between 1 s and 8 s, i. e. for optical energies Q in the range 0.12 mJ – 12.4 mJ. This is shown in figure 2.

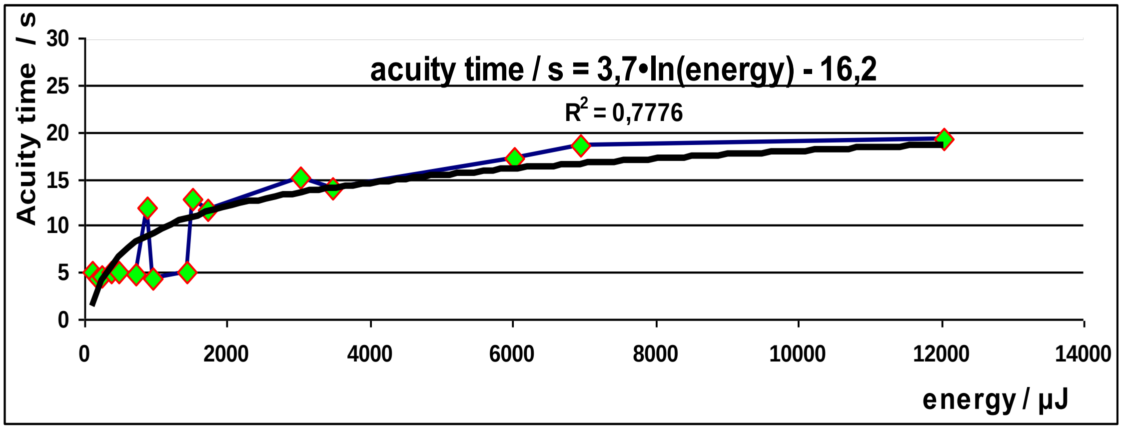

Figure 2. Recovery of acuity (acuity time) as a function of optical energy; light source: green LED (λ = 530 nm), diamonds represent a total of 48 measurement values (mod. [7, 8])

The results achieved for exposure durations of 0.25 s and 1 s with various coloured LEDs show that:

- a relatively large spread exists due to individual perception,
- a rapid rise is distinguishable especially for the green LED,
- green shows the largest impairment time, and
- white LEDs produce larger recovery times than royal blue LEDs, although in principle white LEDs contain a blue LED whose emission is converted in a special phosphor into a broadband radiation in order to result in white via additive colour mixture.

For a more detailed discussion of the results obtained in these special investigations the reader is referred to already published data [8]. Figure 3 shows an example of experimentally achieved results for 3 coloured and a white HB-LED where the exposure duration was chosen to be 0.25 s.

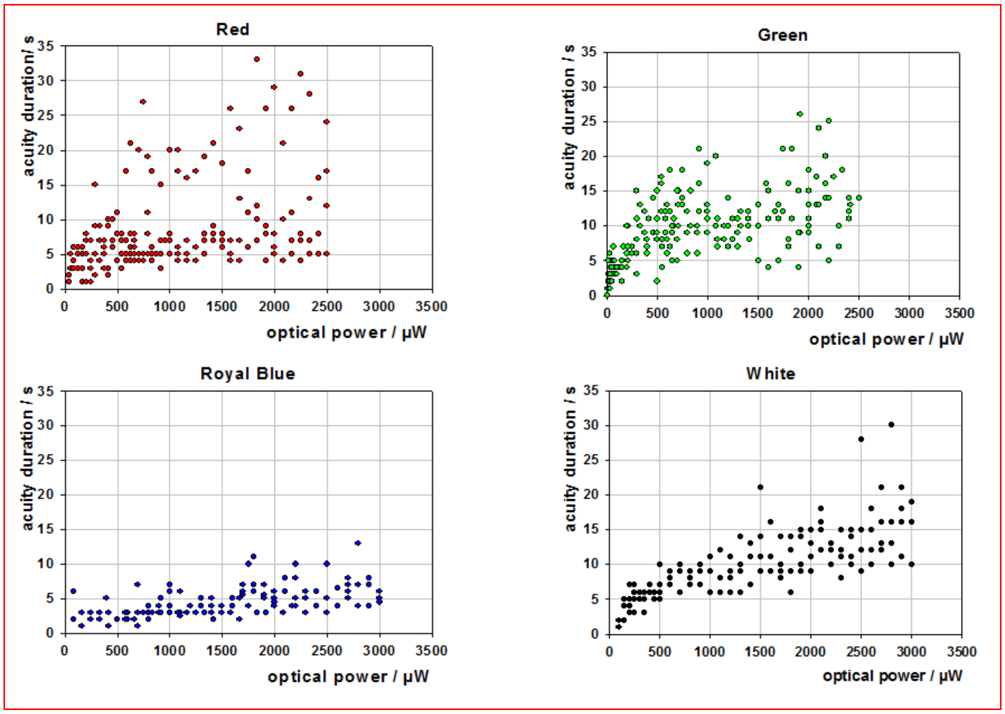

Figure 3. Acuity duration (acuity recovery times) for 3 coloured and a white HB-LEDs (t_{exp} = 0.25 s) as a function of optical power; each mark represents a measurement point

Disability thresholds as a function of exposure duration have been searched and wavelength-dependent values have been found for both laser and LED radiation. In the case of a laser at 632.8 nm a threshold at about 10 µW has been found in 12 subjects for an exposure duration of 0.25 s, which is equivalent to 0,0025 mJ = 2.5 µJ. This is shown in fig. 4. This value is in good agreement with the theoretically derived value of about 5.2 µW in eq. (2) for this wavelength, although it is based on a different study design. The threshold value is at about 1 % of the allowed power level for laser class 2.

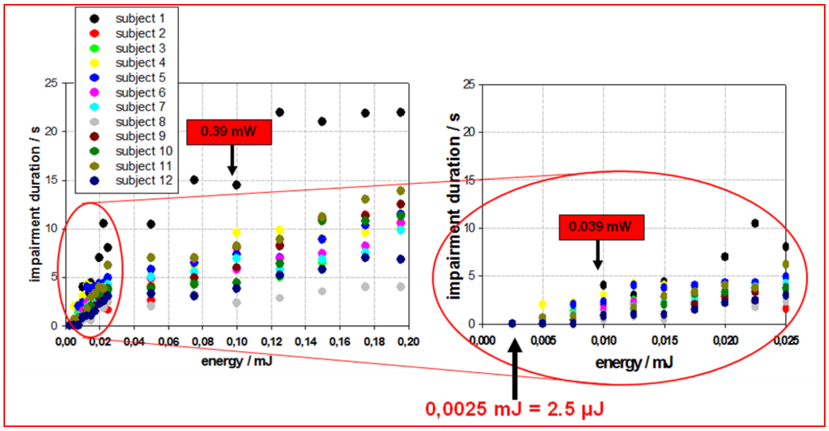

Figure 4. Threshold behaviour: He-Ne Laser (λ = 632.8 nm, t_{exp} = 0.25 s), class 1 limit and 1/10th for comparison

In the case of a green laser (λ = 532 nm) the threshold is well below 10 µW for an exposure duration of 0.25 s (not shown), but could not be found with the applied measurement set-up sufficiently correct. For an exposure duration of 1 s the threshold is even lower. Figure 5 shows a comparison between a red and green laser, where different threshold and saturation values can be found.

Similar results have been achieved for the threshold behaviour for HB-LEDs. A summary for the investigated 4 HB-LEDs is shown in figure 6.

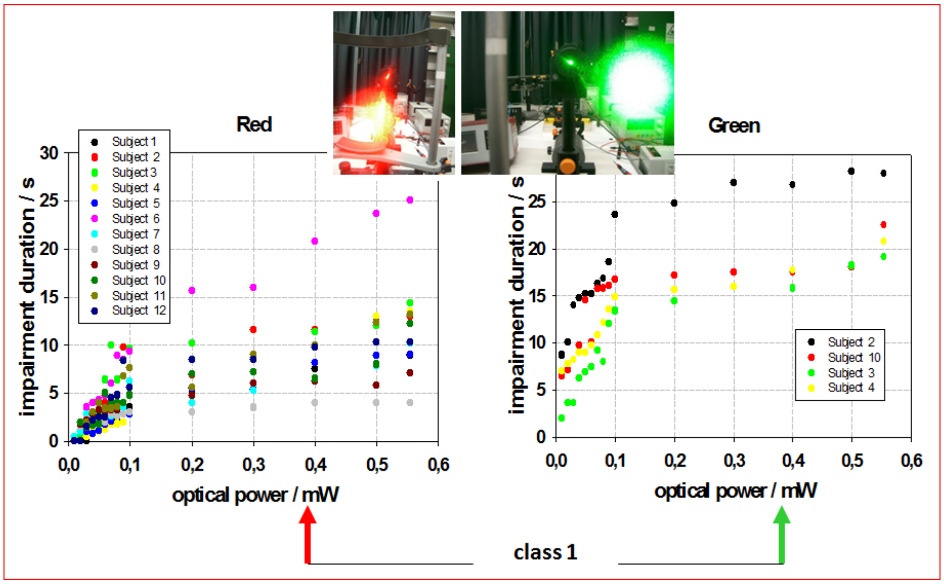

Figure 5. Saturation behaviour for 2 different lasers, λ = 632.8 nm vs λ = 532 nm) – exposure duration: 1 s

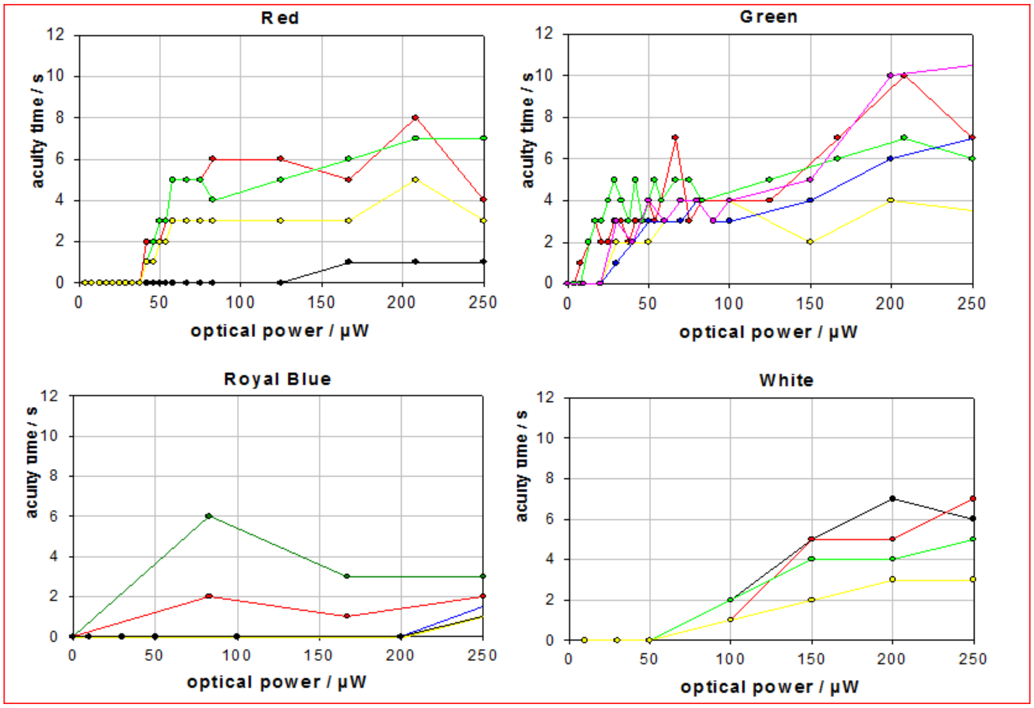

Figure 6. Threshold behaviour for 3 coloured and a white HB-LED – exposure duration: 0.25 s,

Threshold values differ for the various coloured LEDs but might be between about 10 µW and 50 µW in the case of an exposure duration of 0.25 s and exhibit a large individual variety. The main results thus far might be summarized as shown in table 2.

Table 2. Overview of the characteristics of bright light sources as regards temporary blinding

Relatively short exposure durations result in remarkable disturbance of visual functions
Relatively low power or energy densities produce significant impairment
Longer exposure durations are equivalent to stronger impairment, but the relation is not linear
A saturation behaviour is observable
532 nm produces a higher impact compared to 632.8 nm for laser radiation
Individual differences in the impaired visual functions have been found (up to a factor of about 8!)

4. Discussion

It is very good news that there have been very few serious retinal injuries from laser radiation at the workplace and for the general population as well.

According to the classification system in IEC 60825-1 a class 2 laser is a low-risk laser, which might become hazardous only if a person stares into such a beam for a sufficiently long duration. Since the eyes are not in danger as far as accidental and short-term exposure is regarded, laser products of class 2 may be applied without any additional protective measures if it is ensured that neither a deliberate intrabeam viewing of more than 0,25 s nor a repeated intrabeam viewing into a specular reflected laser beam could happen.

Laser safety philosophy for low power laser was mainly based on aversion responses including the blink reflex and the description of laser class 2 and 2M in the international laser product standard IEC 60825-1 implicated this approach for the case of short intrabeam viewing.

For the exposure of the eye to a continuous wave (CW) laser an aversion response time of 0.25 s was recommended as an adequate hazard criterion, if purposeful staring into a visible laser beam was neither intended nor anticipated. There was a strong belief in aversion responses and especially in the blink reflex as a reliable physiological reaction if a bright light is viewed. Therefore in the “summary of the manufacturer's requirements” in 2nd edition of IEC 60825-1 a class-2 laser is still a “low power laser”, where eye protection is normally afforded by aversion responses.

In extensive studies it has been shown in a total of 2,650 volunteers that the optical radiation from a class-2 laser or a high-brightness LED is not sufficient to stimulate more than about 20 % of people to respond with a blink reflex [9-11]. In addition it has been shown with about 1,200 volunteers that aversion responses in terms of head movements and eye closure, which protect the eyes, occur in less than 10 %, i.e. even less frequent compared to the blink reflex. The aversion response investigations were done with volunteers in lab and field trials where the head was unrestrained.

In the case of an LED-array, which represents a large extended source, the frequency of natural aversion responses increases up to about 50 % [10-12], but concerning the potential hazards it is certainly true that a laser poses a higher risk compared to LEDs.

These findings do not state that class 2 laser are no longer safe, but that users of such lasers should be instructed to perform active protective reactions, i. e. close the eyes actively and avert the head in the case of intrabeam viewing as soon as possible. These measures can increase the safety of laser class 2 sufficiently and prevent a violation of the MPE values.

In order to figure out the influence, which results from the degree of knowledge a person gets carrying out the respective test, investigations have been done in a comparative study, where part of the test persons became informed about the intended test procedure before the actual test was performed and a control group has been uninformed. In addition volunteers have been instructed on the purpose of the special trial and asked to perform active protective reactions in the case of an unexpected intrabeam viewing of a laser beam in order to estimate the reaction times and frequencies of the various physiological behavioural patterns.

In contrast to the results obtained with 316 uninformed persons, where only about 7 % showed a blink reflex, it was found in a field trial with 205 persons, which got the instruction to perform active protective reactions, that up to 34.4 % were able close their eyes or move their head within 240 ms and up to 74.4 % within a second [13, 14].

In order to eliminate nearly all cases where exceeding of the ELVs might happen, active protective measures such as those given in the adapted and detailed descriptions for Class 2 and 2M in the 2nd edition of IEC 60825-1 are strongly recommended to prevent any hazard that might result from omission of the expected natural physiological behaviour and prolonged exposure.

The findings concerning aversion responses including the blink reflex have been accounted for with the additional information that users are instructed by labeling not to stare into the beam, i.e. to perform active protective reactions by moving the head or closing the eyes and to avoid continued intentional intrabeam viewing. Proposals how to deal with the safety of low power lasers belonging to class 2 or 2M according to IEC 60825-1 are given in another publication [15], especially taking into account the provisions aimed at avoiding or reducing risks pursuant to the Directive 2006/25/EC.

Even if the real time duration an eye is exposed when intrabeam viewing happens or a reflected beam irradiates the eye is below, let’s say, a second or even below a quarter of a second like in the case of a blink reflex, such an exposure duration is certainly to long in order to prevent the described effects arising due to temporary blinding. This is especially true, since even relatively short irradiations suffice in order to yield long lasting afterimages.

Neither the exposure limit values on which the accessible emission limits for laser classes are based nor the broadband exposure limit values which can be found in the respective risk group allocation are related in a simple way with the degree of impairment due to temporary blinding from bright artificial light sources.

Especially due to improved knowledge from new scientific investigations which have been completed in the last decade and due to experimental and practical experience gained with modern artificial optical sources temporary blinding achieved increasing interest in dealing with bright light sources. In addition as far as lasers are concerned the accessible emission limits (AEL), which characterize the respective laser class, have been increased especially for wavelengths in the visible part of the optical spectrum. Putting these together it is not surprising that IEC 60825-1 points out in its description of the various classes in the informative annex therefore that “*intrabeam viewing of Class-1 laser products which emit visible radiant energy may still produce dazzling visual effects, particularly in low ambient light*”. As far as the application of the classes 2, 2M and 3R is concerned this standard clearly states “*However, dazzle, flash-blindness and afterimages may be caused by a beam from a Class 2, 2M or 3R (in the visible wavelength range) laser product, particularly under low ambient light conditions. This may have indirect general safety implications resulting from temporary disturbance of vision or from startle reactions. Such visual disturbances could be of particular concern connected with performing safety-critical operations such as working with machines or at height, with high voltages or driving*.” [3].

Although these are only recommendations, which should be included in the information for use, this clearly shows that the previous safety philosophy for lasers has been augmented.

In the classification scheme of IEC 62471 [16] for lamps and lamp systems neither dazzle nor glare nor flash-blindness nor afterimage is not even mentioned, i. e. temporary blinding is not considered as a potential risk for the respective lamp groups, namely Exempt group, Risk group 1, or Risk group 2. IEC 62471 deals only with photobiological hazards and not with temporary effects.

Currently the photobiological safety basis for the Risk Group 2 (Moderate-Risk) classification is that the lamp does not pose a hazard due to the aversion response to very bright light sources. But contrary to this it has been shown convincingly and reported that it is not true for LEDs and even LED arrays in any case that this requirement is met by any lamp that exceeds the limits for Risk Group 1 [17].

Concerning the capability of Class-1 lasers to produce dazzle and glare it has been shown that the occurrence of relatively long lasting afterimages might interfere with visual functions up to 300 s as far as central vision is concerned. This has been found at an applied power which was only 10 % of the upper limit of class 1. Therefore care should be taken not to produce long lasting temporary blinding with this laser class and the respective power levels.

The illustrated results achieved for a laser beam might not be transfered without any check-up to cases where the spot on the retina is much larger as in the case of a collimated laser beam, where the retinal diameter is between 25 µm and 50 µm, but some mean value interrelationship might be expected anyhow.

The threshold value for impairment of reading capability has been found to be at about 2.5 µJ, i. e. optical power levels below about 10 µW do not disturb the efficiency to read as long as the exposure duration is less than a quarter of a second in the case of intrabeam viewing into a red helium-neon laser beam. There seems to be a linear relationship especially between optical energy and impairment duration for very low stimulating optical energies or optical powers and a saturation behaviour was observed for higher levels of irradiation.

In the case of a “green laser beam” there exists a relatively steep increase of impairment as a function of optical energy up to power levels of about 0.1 mW. Time delays between 14 s and 24 s have been determined if the exposure duration was 1 s at a power level of 0.1 mW (figure 5). Above 0.1 mW the increase is much slower and a saturation behaviour might be deduced from the slope of the curves obtained experimentally.

A short exposure duration of 250 ms (“momentary exposure”), which is taken as the so-called aversion response time or often equivalent to the blink reflex time and which is used as the classification time base for class 2, 2M and 3R lasers between 400 nm and 700 nm, results in a disruption between about at least 2.5 s up to 10 s or even 15 s if the power is 0.39 mW (or about 0.1 mJ) [8]). Such an exposure situation can easily be achieved with a class 1 laser in the blink of an eye. Taking into account that aversion responses including the blink reflex do not happen always figure 5 shows that for more realistic exposure durations of 1 s, which certainly might be regarded as somewhat “precautionary”, that a green Class-1 laser at 532 nm results in disruption times between 16 s and 27 s.

It has been found that it is not possible and even not reasonable to specify an exact threshold value, since humans respond differently and individually to a dazzling light. This is depicted in the various measured curves in the figures 4 and 6. Therefore the designation of a mean value does not make sense, although it might be desirable.

A comparison between the two different laser wavelength shows that the impairment curve increases much steeper in the case of the green laser beam (cf. figure 5) and reaches considerably larger values. In addition the comparison of both wavelengths impressively shows that the impairment does not happen proportional to the relation between both spectral visibility values, where a ratio of 0.88314/0.24388 = 3.6 is valid according to the CIE 1931 Standard Colorimetric Observer y2(lambda) data (between 380 nm and 780 nm at 5 nm intervals; [18]), but instead a factor of about 1.5 results from the described investigations. Still higher optical powers produce nearly the same glare for both tested wavelengths, which is probably due to a saturation effect, since at the higher illuminance values the normal photopic range seems to be no longer valid in order to predict the respective effect of temporary blinding on visual functions [8].

Up to now there exists no classification system according to physiological glare and temporary blinding from light sources. Thus the allocation of visible optical sources in blinding groups seems to be necessary. A proposal in order to classify light sources according to the blinding capabilities has been made already and is founded in [19].

Irrespective of the choice of the indication such a classification might be regarded as an appropriate assistance to perform a risk analysis. The benefit should thus put into perspective the doubts that this proposal demands yet another classification in addition to the already established ones for laser products according to IEC 60825-1 [3] and for lamps and lamp systems according to IEC 62471 [16].

The determination of the respective blinding group can be performed using standard or modified visual acuity tests. It has been found that in comparison to the standard ophthalmologic acuity tests, which use either Landolt C-rings or the classic Snellen chart, the capability to read a text or special words is more meaningful compared to the well-known visual acuity tests. It should be taken into account that visual acuity measurement involves more than being able to see the optotypes, i. e. C’s or Snellen letters. It has been found in the above reported investigations that visual acuity is influenced subjectively, especially due to the fact that for example the subject might wait exceedingly long in order to be able to correctly state the location of the gap in the broken ring, and this is completely different if the exercise is to read a given word or text, since one is only able to read, if the words can be read.

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