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Evaluation of corneal and eye lens irradiance for optical aided viewing

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The use of a magnifying lens with a highly divergent laser beam may cause a big increase of the irradiance on the cornea and the eye lens. This study provides the analysis of several cases where the use of a lens lead to a corneal irradiance significantly higher than the naked-eye viewing. The examples analyzed in this study allow determining the factors that represent the increase of the corneal irradiance caused by the use of the lens. The results indicate that these factors of irradiance increase may be close to 100. © *2013 Laser Institute of America*.

Key words: laser safety, optical aided viewing, corneal irradiance, lens irradiance, divergent beam, magnifying lens

I. INTRODUCTION

The use of a magnifying lens to focus objects close to a laser aperture may increase the eye exposure to laser radiation not only for wavelengths within the retinal range, i.e., from 400 nm to 1400 nm, but also for wavelengths outside this range, and in particular from 1400 nm to 4000 nm. In this last case, the use of a lens can give a significant increase of the corneal and lens irradiance, with a consequent possible overexposure of the cornea and the eye lens.

In fact, when the lens is used to focus, in order to find the best focusing distances between the eye and the lens and between the lens and the object to be observed, the position of the lens is varied typically for some seconds. During the movements of the lens, there are ranges of distance where the lens can focus the radiation on or close to the surface of the cornea, giving a corneal irradiance much greater than the unaided-eye condition.

The following considerations apply to the case where a magnifying lens is used.

A. During the movement of the lens to find the better distance to focus, high levels of exposure may occur for seconds, since the movements are usually very slow. Therefore, even a movement of few millimeters may take seconds. Furthermore, in case of pulses, tenths of seconds or less are enough to exceed the Maximum Permissible Exposure (MPE) indicated in IEC EN60825-1.[1]

B. The situations where the use of magnifying lens outside the retinal region is much more critical than the unaided-eye are frequent. In fact, these situations include (but are not limited to) the examples below described. In particular, these situations include:
   1. Many values of focal length of the lens: from 25 to 100 mm.
   2. Many values of beam divergence: from 200 to 400 mrad.
   3. Various distances between the source and the lens and between the lens and the eye.

C. Of course, it is possible to find high levels of exposure in cases involving values of focal length, divergence, and distance between the source and the lens and between the lens and the eye other that the ones indicated in this study.

D. The increase of the corneal irradiance due to the use of the magnifying lens is often very high and larger than safety factor. (In any case, the presence of safety should not be considered as a permission to violate MPEs. It should be also considered that the safety factors refer to ED-50 limits,[2] where there are lesions in 50% of cases.)

In this study, the radiation with wavelength range from 1400 to 4000 nm is considered. Since the object of this study is to evaluate the effect of highly divergent laser beams, the apparent source and the physical source of the input beam can be considered located at the beam waist of the beam before the lens.[3] This beam waist is indicated here as "1st beam waist" in this study, while the beam waist of the beam after the lens is indicated as "2nd beam waist."

II. DESCRIPTION OF THE OPTICS

A. Aided eye (use of a magnifying lens)

$\longleftarrow L_2 \longrightarrow$ 2nd beam waist
1st beam waist $\longleftarrow L_1 \longrightarrow$ Lens $\longleftarrow L \longrightarrow$ Eye (cornea)
$\longleftarrow L_{1,eye} \longrightarrow$

f = focal length of the lens, L_1 = distance between the 1st beam waist (source) and the magnifying lens, L_2 = distance between the lens and the 2nd beam waist, L = distance between the lens and the eye, $L_{1,eye}$ = distance between the 1st beam waist and the eye ($L_{1,eye} = L_1 + L$).

B. Unaided-eye

1st beam waist $\longleftarrow L_{100} \longrightarrow$ Eye (cornea)

L_{100} = distance between the 1st beam waist (source) and the eye; it is assumed to be 100 mm.

In the calculations to evaluate the irradiance increase, the minimum beam diameter at the cornea assumed in this study is 3.5 mm, which is the minimum value considered by IEC 60825-1 for wavelengths between 1400 nm and 4000 nm and exposures of 10 s or greater. (This beam diameter value takes into account the effect of eye movements.) The irradiance is evaluated considering the amount of radiation collected by the 3.5 mm diameter aperture, in accordance with IEC 60825-1.

However, in case of exposure less than 10 s, IEC 60825-1 considers smaller beam diameters, depending on exposure duration. For example, in case of exposures less than 0.35 s (e.g., in case of pulsed radiation), IEC 60825-1 considers a minimum beam diameter of 1 mm. If the minimum beam diameter is assumed to be 1 mm, as well as the diameter aperture, the corneal irradiance increase caused by the use of the lens can sometimes reach factors greater than the ones indicated in the Tables I and II (in some cases the factors become more than 10 times greater), especially when the use of the lens gives a very small corneal beam diameter (e.g., much less than 3.5 mm).

In the evaluation of viewing with the lens, the coupling factor (see "IV Coupling Factor") given by the lens diameter is also considered. Two f-numbers are considered: 1 and 2. When f-number is 1, the lens aperture diameter is equal to the focal length; when the f-number is 2, the lens aperture diameter is 1/2 of the focal length. Therefore, in the case of viewing with the lens, the irradiance value is multiplied by both the coupling factor given by the lens aperture and the coupling factor given by the 3.5 mm aperture. The Gaussian beam profile is considered in present work.

III. APPLICATION OF THE GAUSSIAN BEAM PROPAGATION

Applying the Gaussian beam propagation[3] to beams in the case of aided viewing, the beam waist may be considered located at the laser source. The beam diameter at the lens, d_{lens}, is given by

$$d_{\text{lens}} = d_{01}\left(1 + \frac{L_1}{Z_{R1}^2}\right)^{1/2}, \tag{1}$$

$$d_{01} = \frac{2\,\lambda\,M^2}{\pi\,\phi_1} \tag{2}$$

$$Z_{R1} = \frac{\pi\,d_0^2}{2\,M^2\,\lambda} \tag{3}$$

where d_{01} = diameter of the 1st beam waist, λ = beam wavelength, ϕ_1 = beam divergence before the lens, M^2 = beam quality factor, and Z_{R1} = Rayleigh length before the lens.

After the lens, the beam has a second beam waist at the distance L_2 from the lens. The distance L_2 and the beam diameter, d_{02}, of the second beam waist are given by

$$L_2 = f + \frac{f^2\,(L_1 - f)}{(L_1 - f)^2 + Z_{R1}^2}, \tag{4}$$

$$d_{02} = \frac{d_{01}\,f}{\sqrt{(L_1 - f)^2 + Z_{R1}^2}}. \tag{5}$$

The beam diameter at the eye, d_{eye}, is given by

$$d_{\text{eye}} = d_{02}\left[1 + \frac{(r_e - r_i)^2}{Z_{R2}^2}\right]^{1/2}, \tag{6}$$

$$Z_{R2} = \frac{\pi\,d_{02}^2}{2\,\lambda\,M^2}. \tag{7}$$

Applying the Gaussian beam propagation to beams in the case of unaided viewing, the beam diameter at the eye, d_{eye}, is given by

$$d_{\text{eye}} = d_{01}\left(1 + \frac{L_{100}}{Z_{R1}^2}\right)^{1/2}. \tag{8}$$

IV. COUPLING FACTOR

For beams with Gaussian profile, the coupling factor, i.e., the ratio between the amount of power collected by the lens or passing through the 3.5 mm aperture and the total power, is given by the following equation:

$$\eta = 1 - e^{-\left(\frac{d}{D}\right)^2}, \tag{9}$$

where η = coupling factor, d = beam diameter at the lens or at the aperture, D = lens diameter or aperture diameter.

In the case of unaided viewing, there is only one coupling, due to the 3.5 mm aperture.

TABLE I. Examples of situations where the use of the lens, with f-number of 1, increases the corneal irradiance at the cornea by a factor 10 or greater.

Increase of corneal irradiance							
				Range of the values of L_1 for which the use of the lens exceeds by a factor 10 or greater the irradiance of the naked eye			
No.	Focal length F (mm)	Input beam divergence ϕ_1 (mrad)	Distance source-eye $L_{1,\text{eye}}$ (mm)	From (mm)	To (mm)	Range size (mm)	Maximum factor
1	25	200	150	24	41	17	33
2	25	300	150	24	41	17	74
3	35	250	150	38	111	73	51
4	35	400	200	37	55	18	128
5	40	250	200	44	71	27	52
6	40	300	250	43	58	15	74
7	50	200	250	58	84	26	33
8	50	350	300	55	72	17	100
9	100	250	400	146	253	107	51
10	100	300	400	145	252	107	72

TABLE II. Examples of situations where the use of the lens, with f-number of 2, increases the corneal irradiance at the cornea by a factor 10 or greater.

Increase of corneal irradiance							
				Range of the values of L_1 for which the use of the lens exceeds by a factor 10 or greater the irradiance of the naked eye			
No.	Focal length F (mm)	Input beam divergence ϕ_1 (mrad)	Distance source-eye $L_{1,eye}$ (mm)	From (mm)	To (mm)	Range size (mm)	Maximum factor
1	25	200	150	24	40	16	33
2	25	300	150	24	39	15	62
3	35	250	150	38	105	67	44
4	35	400	200	38	52	14	82
5	40	250	200	44	68	24	46
6	40	300	250	43	57	14	62
7	50	200	250	58	83	25	32
8	50	350	300	56	70	14	73
9	100	250	400	148	244	96	37
10	100	300	400	150	241	91	43

In the case of the aided viewing, there are both the coupling factor due to the lens size and the coupling factor due to the 3.5 mm aperture. The overall coupling factor is the product of the two coupling factors. The irradiance increase at the cornea is calculated as the ratio between the aided viewing overall coupling factor and the unaided viewing coupling factor. In fact, this ratio is equal to the ratio of the amount of power collected by the 3.5 mm aperture in the two situations.

V. APPLICATION OF THE GEOMETRIC OPTICS

The propagation of laser beams is described by the Gaussian beam propagation. However, since the values of the source divergence considered in this study is very high, the propagation of such beams can be adequately described also using the geometric optics, considering the location of the beam waist as location of the physical source. This approach simplifies the calculations without giving significant errors.[4]

Applying the geometric optics in the case of aided viewing, the value of L_2 can be considered the distance of the image of the source from the lens, and can be calculated using the thin lens equation,

$$L_2 = \frac{1}{\frac{1}{f} - \frac{1}{L_1}}. \tag{10}$$

The beam diameter at the lens, d_{lens}, the beam divergence after the lens, ϕ_2, and the beam diameter at the eye, d_{eye}, can be calculated as follows:

$$d_{\text{lens}} = L_1\, \phi_1, \tag{11}$$

$$\phi_2 = \frac{d_{\text{lens}}}{L_2}, \tag{12}$$

$$d_{\text{eye}} = |L - L_2|\, \phi_2. \tag{13}$$

VI. SUMMARY OF THE RESULTS

The increase of the corneal irradiance given by the use of the lens is calculated in 20 examples, where the aided viewing is compared with the unaided viewing. The analysis is on four cases, which are the combination of two values of wavelength, 1400 and 4000 nm, and two values of beam quality factor, 1 and 10. The results are the same for the four cases, and are summarized in Tables I and II. In Tables I and II, there are the ranges of distances giving an increase of irradiance of 10 times or more. In Table I, the considered f-number is 1, in Table II the considered f-number is 2.

The use of different values of λ and M^2 gives the same results indicated in Tables I and II, or results that are very close to them.

VII. EXAMPLE

The example 1 in Table II, in the case where f-number = 2, $\lambda = 1400$ nm, and $M^2 = 1$, is described in details below.

$\Phi_1 = 200$ mrad
$f = 25$ mm
$L_{1,\text{eye}} = 150$ mm
For example, if $L_1 = 30$ mm
Then
$L = 120$ mm
$L_2 = 150$ mm

A. Aided-eye viewing

Considering the f-number equal to 2, the lens diameter is 25/2 mm = 12.5 mm. The beam diameter at the lens, d_{lens}, is 6.0 mm, so the coupling factor due to the lens size is 0.9870. Using the lens, the beam diameter at the cornea, d_{eye}, is 1.2 mm, so the coupling factor due to the 3.5 mm aperture is 0.9998. The resulting coupling factor is $0.9870 \times 0.9998 = 0.9868$.

B. Unaided-eye viewing

Considering the eye at 100 mm distance from the source, i.e., $L_{1,\text{eye}} = 100$ mm, the beam diameter at the cornea, d_{eye}, is 20.0 mm, so the coupling factor due to the 3.5 mm aperture is 0.0302.

C. Irradiance increase

The irradiance increase is the ratio between the aided eye viewing coupling factor and the unaided-eye viewing coupling factor is $0.9868/0.0302 = 32.6755$, i.e., about 33.

The significant increase of the cornea irradiance is not limited to one particular value of L_1. In fact, for all values of L_1 between 21 mm and 45 mm (range of 24 mm) the increase of corneal irradiance is given by a factor varying from 5 to 33, and for all values of L_1 between 24 mm and 40 mm (range of 16 mm) the increase of corneal irradiance is given by a factor varying from 10 to 33.

VIII. CONCLUSIONS

The use of a lens near a laser aperture increases the exposure also outside the range of 400 nm to 1400 nm. The MPEs are often exceeded by very high factors, sometimes close to 100. It should be considered that in case of pulsed lasers the situations are more critical than for continuous wave lasers, because in that last case the safety factors are greater.[5]

If a lens is used, the probability to have the eye and the lens in positions giving high values of corneal irradiance is not negligible. In fact, during its use, the lens is moved back and forward to find the best point to focus, and during this movement the lens often may be in positions giving the high corneal irradiance, as indicated in the examples of the tables above reported.

The lens may be kept at the critical distances for a significantly long time. In fact, it may be used to focus the laser aperture, or an object close to the laser aperture. In those cases, the possibility have a high irradiance on the eye is present even if the source is recessed, i.e., farther than the laser aperture.

Finally, it should be considered that the high levels of exposure above described may occur using lenses that are very common and diffused in the market.

In conclusion, the use of a lens to magnify the beam or anything close to the beam aperture can result in corneal and/or lens irradiance greater than MPEs, even if the laser is Class 1 or Class 1M. Therefore, the use of magnifying lens close to a laser beam should be avoided in any case.

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