Review of exposure limits and experimental data for corneal and lenticular damage from short pulsed UV and IR laser radiation

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Laser exposure limits as promulgated by the International Commission on Non-Ionizing Radiation Protection are compared to relevant experimental animal injury data for cornea and lens exposure in the nanosecond to microsecond pulse duration regime in both the ultraviolet (UV) and infrared spectral ranges. In the UV spectral range, thermal and photochemical damage mechanisms compete and thresholds must be carefully distinguished as a function of wavelength and pulse duration. The thermal UV damage data are compared with levels inferred from CO_2 radiation thresholds and it is shown that the reduction factors between experimental data for thermal injury and the corresponding exposure limits appear to be unnecessarily high. The lack of data for nanosecond exposures for wavelengths below 355 nm is identified. Available experimental data for infrared radiation (1.4–4 μm) can be fitted well with an inverse-absorption curve for saline. The exposure limits roughly follow the absorption curve with a varying degree of safety scaling factor. A lack of experimental threshold data is identified for wavelengths around the 3 μm absorption peak for water absorption. The inverse curve for the spectral absorption of water would suggest a rather low threshold for a biological effect at 3 μm. *© 2008 Laser Institute of America.*

Key words: laser safety, MPE, exposure limit, eye, cornea, lens, ultraviolet, infrared, pulse

I. INTRODUCTION

Exposure limits (EL) for ocular exposure to laser radiation are defined at the international level by (ICNIRP) the International Commission on Non-Ionizing Radiation Protection.[1,2] Other documents, standards and regulations either adopt the ICNIRP limits (IEC 60825-1,[3] IEC TR 60825-14,[4] EU Directive "Optical Radiation"[5]) or, if nationally defined, are usually well harmonized with the ICNIRP set of exposure limits (ANSI Z136.1[6]). The IEC and ANSI laser safety standards use the term "Maximum Permissible Exposure" (MPE) instead of "exposure limits." Since MPE is more widely used, in this review we will use the term MPE generally.

As a general principal of photobiology, radiation needs to be absorbed in a tissue to affect it. Correspondingly, the part of the eye at risk for a given exposure depends strongly on the wavelength of the incident radiation: the wavelength range of 400–1400 nm is termed the retinal hazard region. For wavelengths above and below the retinal hazard region the anterior components of the eye, in particular the lens and the cornea, absorb the radiation and are at risk. However, UV radiation down to wavelengths of perhaps as short as 305 nm may be capable of producing retinal damage in special cases. The interaction can be either thermal, due to heating of the tissue or, with sufficient photon energy, photochemical in nature.[7] Photomechanical damage (such as photoablation of the cornea) can occur for short pulse durations.

The wavelength dependence of photochemical interactions and of the optical absorption properties of the relevant ocular media play a role in determining the dominating interaction mechanism and which tissue is affected. Additionally, the induced temperature rise, and the corresponding potential for thermal damage, depend on the pulse duration as well as the optical absorption properties and heat-flow geometry of the affected tissue.

It should be noted that epithelial corneal injury at or somewhat above threshold exposure levels is fully repaired in a matter of 1–2 days because of the recouperative mecha-

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nisms of the cornea. The lens is less capable of repairing injury and the reported studies of lenticular damage show recovery only from exposures at the lowest energy levels that result in changes.[7–9]

In this paper, we review experimental data and exposure limits for corneal and lenticular damage from short pulsed UV and IR laser radiation, i.e., for the wavelength range below 400 nm and above 1400 nm, and for pulse durations between approximately 1 ns and 1 μs. Ocular damage thresholds for the cornea and retina in the wavelength region of 1300–1400 nm were recently reviewed by Zuclich *et al.*[10] and are not discussed here.

Regarding the usage of units, we use both the "per meter" quantities as well as, especially for injury threshold values, the "per centimeter" quantities. We have attempted to state both values (the alternative one in brackets) where it does not impact the legibility of the text.

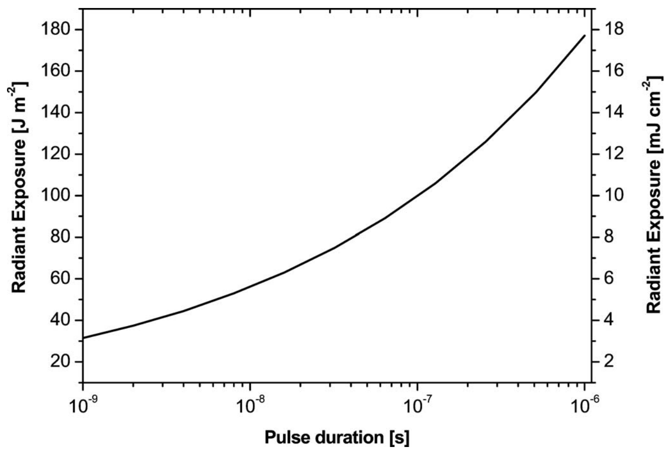

FIG. 1. Function describing the thermal MPE as a function of pulse duration t (in s).

II. UV WAVELENGTHS

A. MPEs

The ICNIRP laser MPEs[1,2] in the ultraviolet wavelength range are given as dual limits to protect the cornea and lens from both photochemical and thermal injury. The photochemical MPE is specified as a constant value of 30 J m^{-2} (3 mJ cm^{-2}) for exposure durations between 1 ns and 30 000 s for wavelengths up to 302.5 nm. For wavelengths between 302.5 and 315 nm the MPE follows a logarithmic dependence on wavelength. For wavelengths between 315 and 400 nm, the photochemical MPE is specified only for exposure durations from 10 s upwards and is a constant value of 10 000 J m^{-2} (1 J cm^{-2}); in that wavelength range, no photochemical MPE is specified for exposure durations less than 10 s. However, in an ICNIRP statement for ocular exposures with optical instruments,[11] that also applies to pulsed laser radiation, the photochemical MPE continues up to a wavelength of 400 nm.

The thermal MPE is given (in J m^{-2}) as 5600 $t^{0.25}$ (or 0.56 $t^{0.25}$ when in J cm^{-2}) where t is the pulse duration. The thermal MPE is defined in the range of 10^{-9} s–10 s; for 10^{-9} s the thermal MPE equals about 30 J m^{-2} (3 mJ cm^{-2}) and for 10 s, it equals about 10 000 J m^{-2} (1 J cm^{-2}). In the ICNIRP guideline revision,[2] the thermal limits are specified for the total UV range of 180–400 nm. For multiple pulses, ICNIRP[2] specifies that the single pulse thermal MPE is to be reduced by a factor $N^{-0.25}$ where N is the number of pulses. Pulses that occur within the time t_{min}, which is specified as 1 ns for the wavelength range of 315–400 nm, are to be counted as one pulse and the sum of the radiant exposure within t_{min} is to be compared to the MPE that is specified for t_{min}. This requirement, however, is actually not needed in the UV wavelength range, since the MPEs for pulse durations less than 1 ns are defined as the maximum level of peak irradiance. This is a conservative approach due to the lack of experimental data. It is also sufficient to deal with multiple pulses that occur within a time window of 1 ns.

In the original ICNIRP laser guidelines,[1] the presentation of the UV dual limits was somewhat ambiguous in terms of wavelength ranges for the thermal MPE, but in the ICNIRP revision,[2] the limits were expressed as dual limits over the full UV range and the reduction factor $N^{-0.25}$ was also required for the thermal MPE in the UV. IEC and ANSI laser safety standards as well as the EU directive all give the same basic values for the photochemical and thermal MPE. However, there are some differences in terms of presentation and the treatment of multiple pulses. The dual limits given in ANSI Z 136.1 are fully identical with the ICNIRP exposure limits of Ref. 2. The laser safety standard IEC 60825-1 Ed2.0 uses a tabular presentation of the MPEs and lists both the photochemical and the thermal MPE in one cell of the table, divided by a diagonal that is representative of a break time T_1. T_1 specifies the maximum pulse duration as a function of wavelength, for which the thermal MPE is applicable (i.e., for pulse durations longer than T_1, the photochemical MPE applies). This presentation is equivalent to the ICNIRP dual limits only for single pulses, since IEC 60825-1 Ed2.0 does not require the $N^{-0.25}$ reduction for multiple pulses. The EU directive in table 2.2 specifies both the thermal and the photochemical MPE, but, for multiple pulses, the presentation could be misinterpreted as the layout is rather reminiscent of the IEC presentation where a break time T_1 is specified as diagonal. Also in the EU Directive, the footnote d of table 2.2 on multiple pulses within t_{min} is not correct since it requires the addition of pulse durations and using that total value for t in the thermal MPEs. However, table 2.6 "Correction for repetitive exposure" gives correct information and is equivalent to the ICNIRP guideline.

The laser photochemical MPE is a conservative simplification of the exposure limit developed for incoherent UV exposure.[12] Short-pulse, thermal damage was not known from conventional, incoherent optical sources. Due to insufficient experimental data for UV wavelengths, the function for the thermal limits was derived from the thresholds for a thermal damage mechanism of a thin layer of corneal tissue from IR-C exposure and is plotted in Fig. 1. The derivation is discussed below on the basis of experimental data available for CO_2 laser exposure.

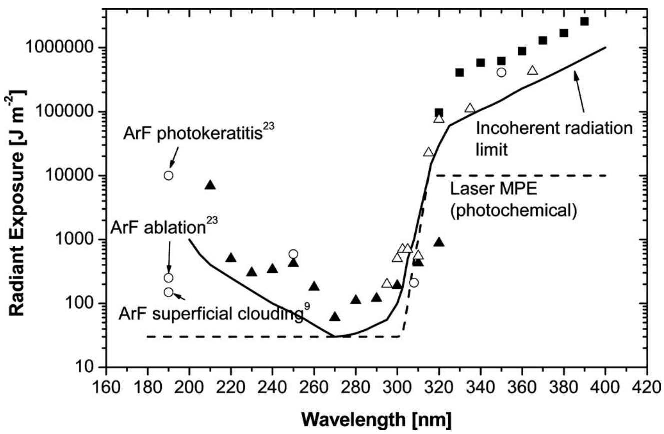

FIG. 2. Experimental photochemical threshold data points for exposure of monkey (see Ref. 13) (squares) and rabbit corneas (Ref. 14 full triangles, Ref. 15 open triangles) to incoherent radiation, as well as thresholds for exposure to short pulsed laser radiation (Refs. 19–23) (circles). The laser data are interpreted as resulting from photochemical damage (photokeratitis) except for the ArF data that are labeled otherwise.

B. Damage of the cornea

Experimental thresholds for photochemical damage of the cornea and lens were obtained as a function of wavelength mainly with incoherent broadband sources.[13–15] Photochemical threshold values for the lens are generally above thresholds for the cornea[9,15] and in the following, only the thresholds for the cornea will be discussed.

As is typical of photochemical damage, the threshold for corneal damage, expressed as radiant exposure (J m^{-2}), does not depend on the pulse duration (or exposure duration) over a very wide range from nanoseconds to thousands of seconds.[16]

Threshold data for photochemical damage (photokeratitis) of the cornea, as found in the literature, is presented in Fig. 2 together with the ICNIRP broadband exposure limit[17] and the laser MPE for photochemical damage.[1] The thresholds refer to an endpoint of barely detectable increased haze observed with a slit lamp biomicrsoscope 24 h after exposure. Also shown in Fig. 2 are two 193 nm data points, labeled with "ablation" and "superficial clouding" which were detectable immediately.

The broadband incoherent radiation limits are directly derived from rabbit, monkey and human data. The older rabbit data were obtained with a bandwidth of[14] 10 nm and later data were obtained with a bandwidth of[15] 5 nm: this change had been made so as to improve the accuracy of the region between 300 and 320 nm where the relationship changes most dramatically. Both data sets shown in Fig. 2 are plotted at the central wavelength points of the 10 or 5 nm band and, due to the finite bandwidth, should be adjusted to the left.[17] The use of a monochromatic laser would steepen the apparent incoherent UV photokeratitis action spectrum for injury thresholds.[18]

The laser photochemical MPE for ultraviolet wavelengths below 302 nm does not follow the pronounced wavelength dependence of the threshold data and the incoherent limits. In the wavelength range of 180–302.5 nm, the laser MPE is constant, and is equal to 30 J m^{-2} (3 mJ cm^{-2}). This value of 30 J m^{-2} is equal to the lowest broadband exposure limit at 270 nm, where the cornea has the greatest sensitivity. For other wavelengths, the broadband exposure limit is higher than the 30 J m^{-2} value.

Also shown in Fig. 2 are data points obtained with excimer laser radiation with a pulse width of about 25 ns.[19–22] The corneal data for 248, 308, and 352 nm compare well with the incoherent radiation data for long-term exposure and photochemical damage. The reported datum point for single pulse threshold at 308 nm appears to be somewhat below the laser MPE but there is some uncertainty about the dimensions of the experimental corneal spot size of the excimer laser exposure.

For wavelengths shorter than about 308 nm and short pulse duration (nanoseconds to tens of nanoseconds), photoablation of the cornea is observed.[9,23] The thresholds in these studies were observed with a slit lamp biomicroscope after staining of the cornea with fluorescein. The threshold values reported for ablation of the cornea with excimer laser pulses of about 20 ns pulse duration were in the range of 250 J m^{-2} for ArF radiation[23] (193 nm, strong absorption in cornea with absorption depths in the range of 1 μm) while superficial clouding of the lens was reported for lower values of[9] 150 J m^{-2}. Reported thresholds for corneal lesions (interpreted to result from photochemical interaction, i.e., photokeratitis) for 248 nm KrF radiation at 248 nm were[9] 590 J m^{-2} (59 mJ cm^{-2}) and for 308 nmXeCl radiation, 210 J m^{-2} (21 mJ cm^{-2}).[9] While the ArF values are below the photochemical limits for broadband radiation (which also apply to longer pulse laser radiation), they are not below the laser thermal MPE of 66 J m^{-2} (6.6 mJ cm^{-2}) for a pulse duration of 20 ns. However, the photochemical laser MPE value of 30 J m^{-2} is clearly unnecessarily low for wavelengths below 270 nm compared to long-term exposure data and the broadband limit. For short pulse exposures, ablation is possible at levels of radiant exposure that are lower than the photochemical broadband limit and therefore the thermal limit is needed to protect against possible ablation damage. This review shows that the UV laser MPEs should be retained as dual limits as in the ICNIRP[2] and ANSI[6] laser safety guidelines. The expression as a single radiant exposure in IEC documents[3,4] is misleading for the case of repetitive-pulse UV exposure. The photochemical limit (which is highly wavelength dependent) and the thermal limit reflect a different additivity of exposure to a train of pulses: photochemical injury follows a total dose dependence and the pulses are fully additive, while the additivity of pulses leading to thermal injury is less pronounced and is for instance expressed as $N^{-0.25}$ where N is the number of pulses.

C. Damage to the lens

For wavelengths in the near UV range, i.e., above about 310 nm, thermal or photochemical damage of the lens is of concern. Photochemical damage thresholds for the lens are

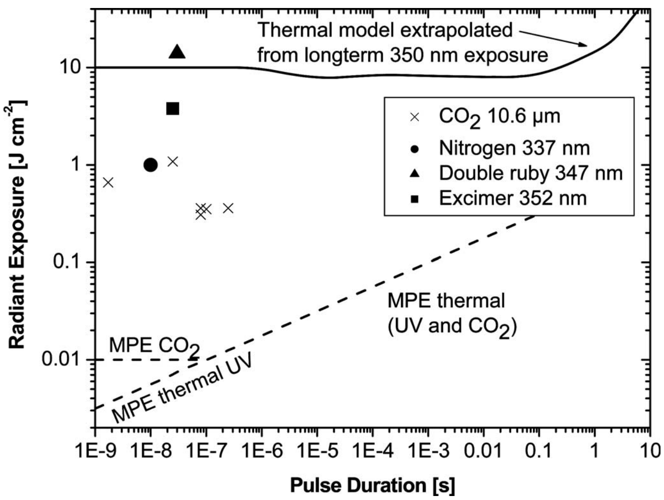

FIG. 3. Available experimental threshold data for thermal damage of the lens for wavelengths above 310 nm. For comparison, the MPE values for CO_2 laser (10.6 μm) and UV wavelengths are also shown.

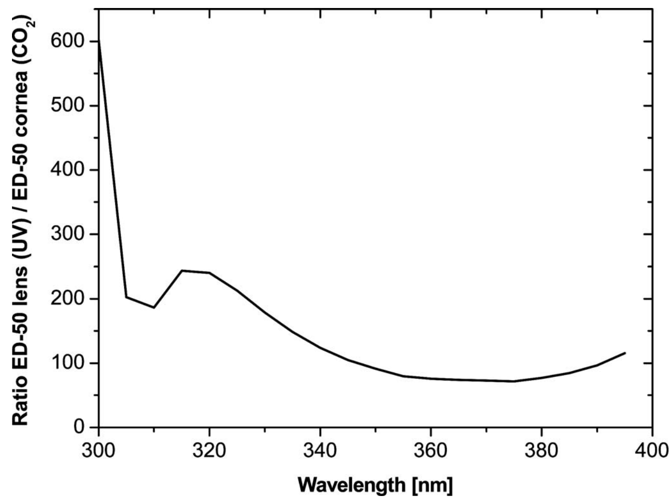

FIG. 4. Estimation of a theoretical factor between the thresholds for the lens in relation to the damage threshold as determined for the cornea for exposure to CO_2 laser radiation. The estimate is based on optical transmittance data for the cornea and the aqueous and absorption depth values for the lens.

above the photochemical threshold values for the cornea,[9,15] hence only thermal damage to the lens needs to be considered for a single-pulse exposure.

Experimental threshold values for thermal damage of the lens by short pulse laser radiation are few. For a wavelength of 337 nm from a nitrogen laser with a pulse duration of 10 ns,[24] the threshold for clouding of a monkey lens was reported to be about 1 J cm^{-2} (value taken from a plot). Another study with a frequency doubled ruby laser with a wavelength of 347 nm and a pulse duration of 30 ns reported a threshold[25] of 14 J cm^{-2}. For multiple pulse exposure to 352 nm, 25 ns excimer laser pulses,[20] a threshold of 15 J cm^{-2} total radiant exposure for four pulses was reported. The endpoint for lenticular damage is a barely detectable clouding of the lens (cataract) upon examination with a slit lamp. For photochemically induced damage (with complete additivity), this threshold value would also apply to a single pulse; for thermally induced damage with the assumption of a $N^{-0.25}$ relationship, a single pulse threshold of 5.3 J cm^{-2} can be inferred (each pulse contributed 3.75 J cm^{-2} to the total threshold dose, and this value corresponds to the single pulse threshold multiplied with $4^{-0.25}$). Additional information on thresholds for short-pulse exposures in the UV can be obtained by extrapolation from exposures to 350 nm radiation with a range of pulse durations from 100 μs to seconds.[9] When the data and the extrapolation are plotted in terms of J cm^{-2}, it can be seen (Fig. 3) that the threshold is relatively constant with time and about 6–10 J cm^{-2}. For multiple pulse exposure, as with any cw exposure, the UV photochemical cataractogenesis action-spectrum studies of Pitts *et al.*[15] for incoherent exposures to narrow-band monochromator radiation need to be considered. They found thresholds for transient opacities of the order of 0.3 J cm^{-2} and permanent opacities at approximately 0.5 J cm^{-2} at 305 nm and a very narrow action spectrum for acute, photochemical cataractogenesis ranging between 295 and 325 nm.

The thermal threshold limit for the lens can be bracketed to the lower end by a comparison with the corneal limit for CO_2 laser radiation (10.6 μm). The absorption depth of CO_2 laser radiation in the cornea is only a few micrometers, while that for the lens for UV radiation will be much larger.[26] Consequently, the laser energy will be absorbed in a larger volume and this results in a comparably smaller temperature rise. Based upon the assumptions that the temperature scales linearly with the energy absorbed in a given volume, and that the critical temperature for the cornea is the same as for the lens, it can be estimated that the damage threshold for the lens should be about a factor 100–200 higher than the threshold for the cornea, as is shown in Fig. 4.

This estimate is very rough and the assumptions may not be justified.[1] However, it can be generally argued that the threshold for thermal damage to the lens should not be lower than the threshold of the cornea for short pulse CO_2 laser radiation. For comparison, threshold data as reported in the literature for CO_2 laser radiation for different pulse durations are shown in Fig. 3 as crosses (for references see section on infrared damage threshold values). Some of the CO_2 threshold data lie in the range of the UV-Nitrogen datum point, but others lie a factor of 3 below this.

Also shown in Fig. 3 are the MPE values for CO_2 laser radiation and the thermal UV MPE values. The MPE for the CO_2 laser wavelength only decreases down to 100 ns and then, for shorter pulse durations, assumes a constant radiant exposure value, as would be expected for a time domain which is comparable to the thermal relaxation duration. However, the thermal UV MPE values decrease steadily even for pulse durations shorter than 100 ns. The larger absorbing volume of lens tissue for near UV wavelengths in comparison to the shallower absorption depth for the CO_2

[1]For instance, a larger thermal relaxation time due to a larger volume also means that the elevated temperature does not diffuse as quickly as for superficial heating, and not only the level of temperature but also the temperature-time history is important for thermal damage.

TABLE I. Selected MPEs for infrared wavelengths greater than 1400 nm and pulse durations in the range of 1 ns to 1 μs.

Wavelength	Exposure duration	MPE ($J m^{-2}$)	MPE ($mJ cm^{-2}$)
1400–1500 nm	10^{-9}–10^{-3} s	1000	100
1500–1800 nm	10^{-9}–10 s	10 000	1000
1800–2600 nm	10^{-9}–10^{-3} s	1000	100
2600–10^6 nm:	10^{-9}–10^{-7} s	100	10
	10^{-7}–10 s	5600 $t^{0.25}$	560 $t^{0.25}$

laser wavelength, would, however, point to a range of constant thermal UV MPE values at longer pulse durations than is the case for CO_2 laser wavelength MPEs.

The threshold for CO_2 radiation exhibits no marked dependence on pulse duration for durations as long as 1 μs, and this can also be understood on the basis of thermal relaxation times. The safety factor for CO_2 laser radiation, in comparison to the CO_2 MPE, is in the range of 30–100 and the safety factor for thermal damage to the lens for pulse durations of 10 ns is in the range of 80–300.

D. Discussion

For wavelengths in the near UV range, i.e., for wavelengths between about 310 and 400 nm, thermal damage to the lens seems to be the dominating effect for exposure durations between 1 ns and at least 1 μs. Within this time domain, contrary to the thermal MPEs, the experimental data for thermal damage do not seem to depend on the pulse duration; however, there is considerable uncertainty and spread in the values of the data. For a large volume absorber, such as the lens, a temporal dependence for pulsed exposures would not be expected, as is exemplified by the laser MPEs for 1500 nm laser radiation.

In order to bracket possible values, the thermal model data shown in Fig. 3 could be adopted as an upper boundary, even though one threshold datum point, for 347 nm radiation, was reported with somewhat higher values. As a lower boundary, the lowest corneal damage threshold values reported for CO_2 laser radiation may be adopted, which, based on much shallower absorption depths for the CO_2 radiation, present a theoretical lower boundary for exposure to the lens.

Below 302.5 nm, the threshold values mirror the dominance of the ablation and photochemical injury mechanism that the thermal laser MPE appropriately reflects. These rather low values demonstrate the potential of short pulse laser radiation to cause ablation of the surface of the cornea. When the limits are specified as full dual limits (i.e., the thermal MPEs for the full wavelength range of 180–400 nm as is the case in the ICNIRP and ANSI documents but not in IEC 60825-1 Ed2.0) then the photochemical laser MPEs for wavelengths less than 270 nm could be changed to be wavelength dependent equivalent to the broadband MPEs.

Therefore it appears that for short pulse exposure, the dominating effects can be identified and if it were not for the additivity of multiple pulses, there would not be a need for dual exposure limits. More importantly, the current thermal MPE for exposure in the near UV, i.e., for wavelengths above about 310 nm, appears unnecessarily low. While there is considerable spread in the threshold values reported in studies of corneal injury from ultraviolet radiation, for a given experimental data set, the thresholds and the slope of the probit plot are remarkably well defined. This slope of the experimental dose response curve is often so steep that, apparently, it is frequently not calculated, or at least not reported. Review of the studies of Bargeron *et al.*[27,28] and Peppers *et al.*[29] for infrared radiation and Zuclich[9] for the ultraviolet range, shows that slope values (characterizing how the spread out of the dose-response curve is; a slope of 1 represents a sharp step function) in the range of 1.05–1.2 are typical. Thus for defining exposure limits, the low spread due to variability can be accounted for and large safety factors are unnecessary.[30]

The steepness of the photochemically initiated photokeratitis and photocataractogenesis in the 300–320 nm spectral region could be accurately refined by using a tunable, cw UV laser or several discrete laser wavelengths in this region.

Historically, interest in improving the accuracy of the MPEs for near UV short pulse exposure was limited due to the sparse availability and usage of corresponding sources; this might change with recent developments such as the *q*-switched frequency tripled Nd:YAG laser as producing a wavelength of 355 nm. Experimental studies with this kind of laser would allow the unnecessarily low thermal MPE values in the near UV range to be raised.

III. INFRARED WAVELENGTHS ($\lambda > 1.4$ μm)

A. Introduction

Exposure to laser radiation in the infrared (IR) wavelength range outside the retinal hazard spectral region, i.e., between 1.4 and 1000 μm (1 mm), can result in corneal injury. Experimental threshold studies have identified only thermal and thermomechanical injury mechanisms. Accordingly, experimental injury thresholds (as discussed below) and MPE values generally follow the wavelength dependence of the penetration depth of radiation into the cornea.[31–33]

B. MPEs

The MPEs depend upon penetration depth of energy into the eye and are grouped into four spectral bands (see Table I) with three different levels of associated MPEs. Radiation with wavelengths from 1400 to 1500 nm and 1800 to

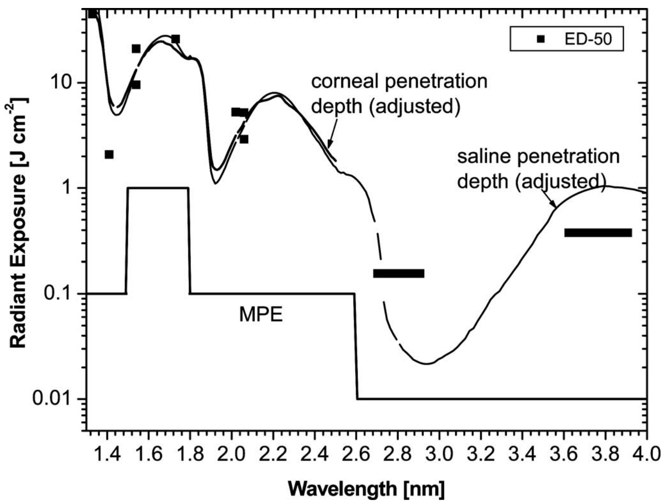

FIG. 5. Experimental threshold data compare well with the absorption depth curve for the cornea and saline, where the absorption depth curves are scaled to fit the experimental data. Also shown are the MPE values for the respective wavelengths for the nanosecond time regime.

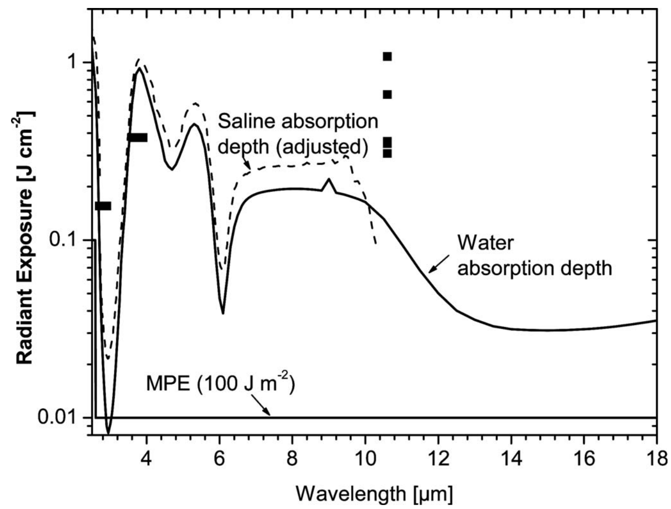

FIG. 6. Experimental threshold data in the far infrared wavelength region, especially for CO_2 laser radiation. The experimental threshold data for short pulse CO_2 laser radiation depart from the general tendency of the wavelength dependence of saline/water absorption depth. Also shown is the MPE for the respective wavelengths.

2600 nm have moderate penetration into the cornea. Radiation with wavelengths between 1500 and 1800 nm penetrates deeply into the cornea and even well into the aqueous, with the consequence that the greater absorbing volume distributes the dose and greatly raises the threshold of injury for pulsed lasers.[31] For this reason, this spectral region is sometimes referred to as the "eye-safe" spectral region, although the eye can still be injured at high exposure doses. The MPEs for pulsed lasers are therefore highest in the 1500–1800 nm spectral band. Radiation with wavelengths above 2600 nm is superficially absorbed in the cornea.

In the wavelength range of $2600-10^6$ nm ($2.6-1000$ μm), the dependence of the MPE on the exposure duration for exposures above 100 ns is expressed as $H_{\mathrm{IR}}(t)=5600t^{0.25}$ (H_{IR} in units of J m^{-2}) and reflects the reduction of the threshold due to the reduction in thermal diffusion for shorter exposure durations.

C. Experimental data

In Fig. 5, experimental threshold data for short pulse exposure with wavelengths in the range of 1300–4000 nm are plotted[32] together with an absorption depth curve for the human cornea.[26] The endpoint in these corneal threshold studies is a superficial clouding or whitening of the center of the exposed area of cornea as detected with a slit lamp either 30 min or 1 h after exposure. A comparison with the corresponding absorption curve for saline[26] shows that in the infrared the absorption behavior of the cornea is dominated by water. Also shown are the MPE values for short pulse (nanosecond) exposures.

It can be seen that the general wavelength dependence of the experimental threshold data follow the wavelength dependence of the absorption depth very well. This can be related to a thermal damage mechanism where the temperature rise scales directly with the inverse of the absorption depth, i.e., for a large absorption depth, the energy is distributed over a larger volume resulting in smaller temperature rises, which in turn is reflected by higher threshold values.

In Fig. 6, the saline absorption depth curves and the water absorption depth curves[34] are shown for the far infrared wavelength region. The only experimental data available for wavelengths above 4 μm are for 10.6 μm CO_2 laser radiation.

The experimental CO_2 data for short pulses as identified in the literature are summarized in Table II.

The data as reported by Zuclich and Blankenstein[21] were corrected by a factor of 2 according to the definition of the beam diameter specification, which was $1/e^2$ in the original publication and should be 1/e for the calculation of the peak exposure.[35] The threshold value reported by Mueller and Ham[36] for 1.4 ns pulse duration detected 48 hours after exposure is considerably lower than threshold data of comparable pulse durations, such as the 1.7 ns threshold value from Zuclich (the Mueller, Ham datum is not shown in FIG. 6). There has been discussion[37,38] about the validity of the experimental data as reported by Mueller and Ham and it is believed that the value was influenced by the experimental technique and difficulties in the calibration of the radiometer. The datum was considered but rejected by the committees which defined the MPE values. However, the other reported threshold values fit well with a theoretical model curve for threshold data as a function of pulse duration which includes pulses of durations up to 10 s.[39].

D. Discussion

The MPE values for CO_2 laser radiation have been specified according to a constant radiant exposure model for pulse durations only up to 100 ns, however, the experimental data and the model calculations of Zuclich *et al.*[39] suggest a constant threshold for pulse durations up to about 10 μs or even 100 μs (see also Fig. 3.)

TABLE II. Experimental threshold data for short pulse CO_2 laser radiation exposure.

Author	Pulse duration	Threshold ($J\ m^{-2}$)	Threshold ($mJ\ cm^{-2}$)
Zuclich, Blankenstein[a]	1.7 ns	6600	660
	25 ns	10 800	1080
	250 ns	3600	360
Mueller, Ham[b]	1.4 ns	60	6
Farell *et al.*[c]	80 ns	3600	360
McCally, Bargeron[d]	80 ns	3070	307
Stuck *et al.*[e]	100 ns	3500	350

[a]Reference 21.
[b]Reference 36.
[c]Reference 35.
[d]Reference 42.
[e]Reference 31.

A comparison of the available data shows that the MPEs roughly follow the wavelength dependence of the experimental threshold values, and the safety value between MPEs and thresholds is generally about 10–50. However, when one considers the fit of the saline absorption curve at wavelengths of about 3 μm where water has the strongest absorption, the safety factor would appear to be only about 2, but this can be misleading, since the penetration depth is only of the order of 1 μm. Unfortunately, there are currently limited threshold data available to define this factor more accurately and better define the "far infrared action spectrum" in the 3 μm spectral band and beyond. Fortunately, there has been considerable interest in medical applications of the Er:YAG laser with a wavelength of about 3 μm (2.94 μm) and these studies indicate that ablation occurs only at radiant exposures of the order of 0.1 J cm^2 for nanosecond pulses.[40] Studies in that wavelength region in corneal tissue showed that the surface was only dehydrated as surface water was evaporated.[41] The biological significance of such superficial changes should not be construed as "damage" and the safety margin is considered quite substantial.

For wavelengths above 3.2 μm there is a larger spread in experimental data and a correspondingly larger uncertainty associated with the thresholds. Saline absorption data are only available up to wavelengths of 10 μm and might not be the most appropriate to characterize the properties of the eye in the IR-C (above 3 μm) due to absorption of, for instance, amides, and the water absorption curve should be used as a guide for the wavelength dependence of the laser threshold beyond this with considerable caution, as it is questionable if the optical properties of pure water are truly representative of the absorption of the cornea above 10 μm. Further studies of radiation in the far infrared where absorption depths are small would be helpful in clarifying the possible effects of ablation, and perhaps allow an increase in the MPE for short pulse exposure.

IV. CONCLUSIONS

A comparison of available experimental data with current ocular laser MPEs for UV and IR exposure to short pulses shows that for wavelengths below about 310 nm the thermal laser MPE as specified by ICNIRP and ANSI is needed to protect against possible photoablative damage of the cornea. The photochemical MPE for wavelengths less than 270 nm is unnecessarily low and could be raised similar to the broadband incoherent exposure limits. The near-UV thermal damage MPE values, when compared to available threshold data for thermal damage of the lens, and to CO_2 laser data for the cornea which can be used to bracket the damage for shallow absorption depths, seem to be unnecessarily low. Available threshold data, however, are scarce and exhibit a considerable spread. Experimental studies, especially for instance with frequency tripled Nd:YAG at a wavelength of 355 nm, will be necessary to reduce the uncertainty. Also, the steepness of the photochemically initiated photokeratitis and photocataractogenesis threshold curve in the 300–320 nm spectral region requires better measurement by using a tuneable, cw UV laser or several discrete laser wavelengths in this region. There is a need to harmonize the thermal UV limits of the IEC documents 60825 Part 1 and Part 14 with the ICNIRP exposure limit guidelines for the condition of multiple pulse exposure.

In the infrared wavelength range up to about 4 μm, experimental threshold values change, wavelength by wavelength, in a similar way to the absorption depth of saline. The MPEs follow the wavelength dependence in a rather crude way, but maintain a safety factor of at least 10, with the possible exception for wavelengths around 2.9 μm where the factor between the fitted saline absorption depth curve and the MPE is only 2. Further experimental studies with Er.YAG laser radiation would be valuable to extend the threshold database. Several reported studies, performed with short-pulsed CO_2 laser radiation, indicate that the safety factor is at least 30, however, the MPE could only be increased following definitive studies regarding ablation effects with potentially lower threshold values.

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