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WAVELENGTH DEPENDENCE OF OCULAR DAMAGE THRESHOLDS IN THE NEAR-IR TO FAR-IR TRANSITION REGION: PROPOSED REVISIONS TO MPEs

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Abstract

This report summarizes the results of a series of IR laser-induced ocular damage studies conducted over the past decade. The studies examined retinal, lens, and corneal effects of laser exposures in the near-IR to far-IR transition region (wavelengths from 1.3-1.4 µm with exposure durations ranging from Q-switched to cw). The corneal and retinal damage thresholds are tabulated for all pulsewidth regimes and the wavelength dependence of the IR thresholds is discussed and contrasted to laser safety standard maximum permissible exposure (MPE) limits. The analysis suggests that the current laser standard MPEs could be beneficially revised to: (1) relax the IR MPEs over wavelength ranges where unusually high safety margins may unintentionally hinder applications of recently developed military and telecommunications laser systems; (2) replace step-function discontinuities in the IR MPEs by continuously varying analytical functions of wavelength and pulsewidth which more closely follow the trends of the experimental retinal and corneal ED_{50} threshold data; and (3) result in an overall simplification of the safety standard MPEs over the wavelength range from 1.2 µm to 2.6 µm. A specific proposal for amending the IR MPEs over this wavelength range is presented.

Introduction

Despite the 1.3-1.4 µm bioeffects studies published earlier by our laboratory [1-7], investigations of laser-tissue interactions in this wavelength range are few in number and there is a paucity of ocular damage threshold data to support laser safety standard [8,9] maximum permissible exposure levels (MPEs). Ocular tissue absorption coefficients vary rapidly with wavelength across the near-IR and the transition region between the near-IR and far-IR spectral ranges. Consequently, the current MPEs vary abruptly and discontinuously across this wavelength range (Figure 1). Due to the absence of ocular damage threshold data at the time the exposure limits were developed, the MPEs around 1.3-1.4 µm were conservatively drawn, erring on the side of caution and unintentionally inhibiting applications using laser sources in this wavelength region.

Our objectives, therefore, have been to augment the ocular damage threshold database in the 1.3-1.4 µm wavelength range and to suggest, where warranted, revisions in the MPEs so that they more closely reflect the trends of the experimental threshold data without discontinuities and widely divergent safety margins across the near-IR to far-IR transition region.

To this end, we first examined the ocular effects following exposure to a continuous wave (cw) Nd:YAG laser operating at either 1.318 µm or 1.356 µm [1,2], and later studied the effects induced by pulsed Neodymium sources emitting at 1.315 µm [5] and 1.319 µm [6,7]. The general conclusions for the exposure conditions studied were that relatively small changes in exposure duration and/or wavelength can substantially alter ED_{50} damage thresholds for the cornea, lens, iris, and retina and may even result in changes in the tissue site(s) exhibiting the lowest damage threshold. In particular, at ~1.315 µm, the cornea proved to be the most sensitive ocular tissue to cw exposures (no retinal effects were observed for 10-s exposure durations) but the retina, lens, and iris all exhibited comparable sensitivity to the cornea with exposure times of 0.1-1 s [1]. The retina was far more sensitive than the other ocular components with sub-millisecond pulse durations [5-7].

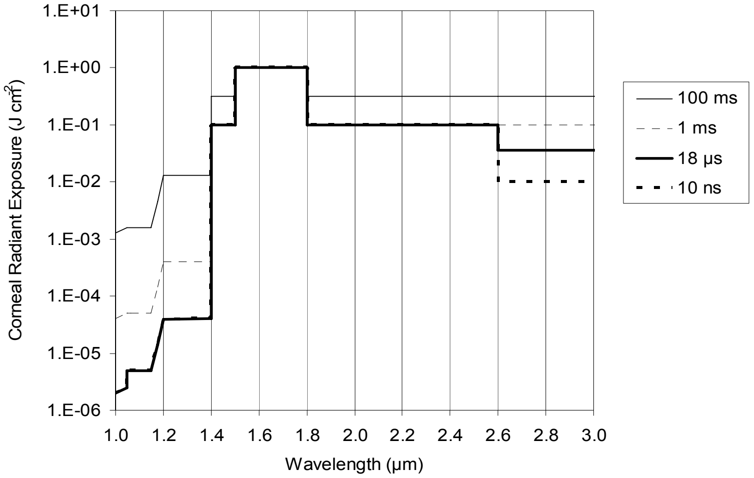

Figure 1. Maximum permissible exposure limits for laser wavelengths from 1 to 3 µm and exposure durations from 10 ns to 100 ms.

The analysis in this report focuses on the wavelength dependence of the retinal and corneal damage thresholds over the near -IR to far-IR transition region and the dramatic variation, with exposure duration, of the relative corneal and retinal sensitivities for given wavelengths within this range. It is the attempt to reconcile these ED_{50} threshold data with the current laser standards which leads to the suggestion of reformulating the IR MPE levels.

ED_{50} Threshold Data

The series of investigations of ocular damage thresholds induced by 1.3-1.4 µm laser radiation [1-7] utilized three Nd laser systems and encompassed a total of four exposure duration regimes from Q-switched to cw. Specific exposure durations for which corneal and/or retinal ED_{50} damage thresholds were determined were 50 ns, 350 µs, 0.28 s and 10 s. In general, rhesus subjects were used for retinal ED_{50} threshold determinations and Dutch Belted rabbits used for corneal exposure studies, although for the 0.28-s exposures, corneal and lens threshold data were collected from both species and retinal effects were observed in the rabbit but not in the rhesus. Retinal damage was not found in either species following 10-s exposures.

Data for ED_{50} threshold determinations were collected by ophthalmoscopic observation of minimum visible lesions (MVLs) at both 1-hr and 24-hr postexposure. Retinal ED_{50}s (in the rhesus) were determined for both macular and paramacular exposure sites. Retinal ED_{50} thresholds were invariably lower when lesion/no lesion readings were collected at 24-hr postexposure than with 1-hr postexposure readings. Macular thresholds were always lower than the corresponding paramacular threshold, usually by a factor of ~2. Corneal ED_{50}s showed no statistically significant differences between the 1-hr and 24-hr postexposure determinations and neither corneal nor retinal MVLs progressed significantly for times beyond 24-hr postexposure. Instances where delayed effects and progression of the extent of ocular damage were observed following suprathreshold laser exposures have been described in detail in earlier publications [2-5].

Table 1summarizes the MVL corneal and retinal ED_{50} thresholds for the four pulsewidth regimes mentioned above. Also displayed in Table 1 are the current laser safety standard MPEs for each wavelength-pulsewidth pairing [8-9] and the ratio of each ED_{50} threshold to the corresponding MPE. It should be noted that some literary license is invoked in assigning the corneal MPEs and the corresponding ED_{50}/MPE ratios in that the existing laser standards are structured as though only retinal damage would be observed with exposure wavelengths $\leq$ 1.4 µm and only corneal effects would be found with wavelengths $\geq$ 1.4 µm. So, as indicated by footnote 2 under Table 1, the corneal MPE for each entry at ~1.315 µm and for each of the four exposure durations is assigned the MPE value associated with that particular exposure duration but with a wavelength of 1.4 µm.

Table 1. ED_{50} vs MPE for 1.315-1.319 µm laser exposures.

Wavelength (µm)	Pulse Duration	Spot Size[1] (mm)	ED50 (J cm^{-2})	MPE [2] (J cm^{-2})	ED50/MPE
1.319	50 ns	0.15	540 (c)	0.1	5400
1.319	50 ns	4.5	0.05 (r)	0.00004	1250
1.315	350 µs	1	42 (c)	0.1	420
1.315	350 µs	5	1 (r)	0.00016	6250
1.318	0.28 s	1	175 (c)	0.41	426
1.318	0.28 s	5	$\geq$ 175(r)	0.028	>6250
1.318	10.0 s	0.8	1890 (c)	1.0	1890
1.318	10.0 s	5	- (r)	0.40	-

(c) = corneal threshold, (r) = retinal threshold

[1] Laser beam diameter incident at cornea.

[2] Corneal MPE for wavelength = 1.4 µm.

Discussion

It is evident from the final column of Table 1 (ED_{50}/MPE ratios) that, within the wavelength range used in these studies, the margin of safety built into existing laser standards far exceeds the nominal value (factor of ten) universally considered as more than adequate to protect against worst-case exposure scenarios. Based on the earlier publications from this laboratory [1-7], the authors have suggested that the MPE levels in the near-IR to far-IR wavelength transition region could be relaxed (in some cases by 2-3 orders of magnitude) while still maintaining adequate margins of safety relative to the body of experimental ED_{50} data.

Formulation of revisions to the IR laser safety standards has proved to be a tedious and delicate affair. The functional dependencies of MPEs on wavelength (λ) and exposure duration (t) are interlaced in such a way that changing the dependence on one parameter, invariably affects (for some exposure conditions) the dependence on the other. An underlying requirement, therefore, in revising the standards and reconciling the permissible exposure limits with the experimental data for wavelengths in the 1.3-1.4 µm range (Table 1), has been to insure that the safety margins are not narrowed for the wavelength-pulsewidth pairings where the margins already reside in an acceptable range. At the same time, the proposed revisions to the MPE levels have sought to address other recognized shortcomings of the existing safety standards. Primary among these is the occurrence of discontinuities or step functions where the current MPEs jump by as much as three to four orders of magnitude at certain wavelengths (e.g., see Figure 1). The proposed revisions would replace many of the step functions by continuously varying analytical functions, which are, in part, wavelength- and pulsewidth-dependent functions already incorporated into the current laser standards. Thus, the proposed revisions, by extrapolating existing features of the current standards and by analysing recently published IR ED_{50} threshold data and the observed wavelength-dependent trends in these data, seek to both eliminate discontinuities in the MPEs and to more faithfully track the experimentally determined trends in the retinal and corneal ED_{50} damage thresholds.

Figures 2 and 3 summarize, respectively, retinal ED_{50} damage thresholds for wavelengths up to ~1.3 µm and corneal ED_{50} threshold data for wavelengths longer than ~1.3 µm [10-11]. Figure 2 displays the wavelength dependence of retinal ED_{50} damage thresholds (light dashed lines) as well as the current MPEs (solid lines) for both short (ns) and long (0.1 s) pulsewidths. A feature of the current MPEs shared by all exposure durations (from 10^{-13} s to 3×10^{4} s) is the wavelength-dependent term, $c \times 10^{18(\lambda-1.15)}$, which defines the MPE for wavelengths from 1.15 to 1.20 µm ('c' varies with exposure duration). The proposed MPE lines plotted in Figure 2, suggest that extrapolating this wavelength dependent term to perhaps ~1.3 or 1.4 µm would yield MPEs which closely follow the wavelength trends of retinal ED_{50} thresholds, including the ~1.3-µm threshold data summarized in Table 1.

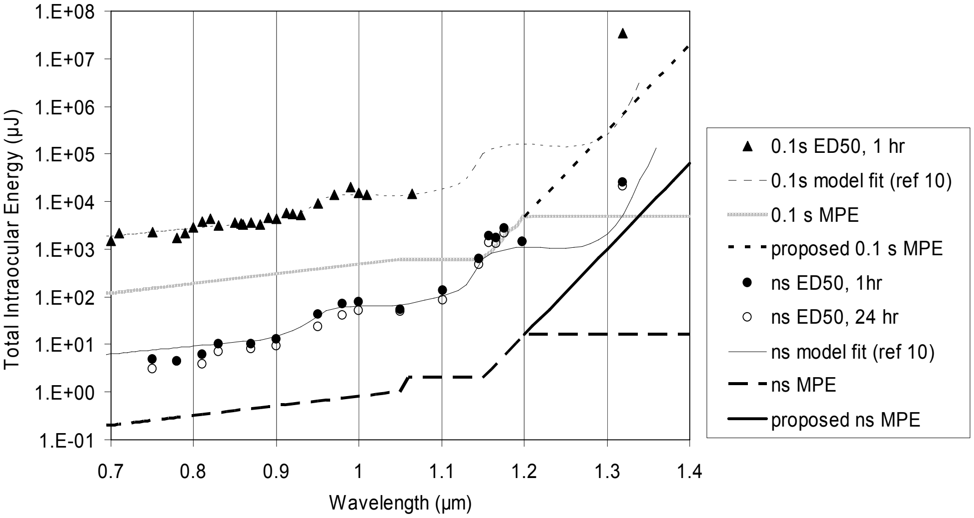

Figure 2. Retinal ED_{50} threshold data and MPEs for 0.7 to 1.4 µm; short (ns) and long (0.1 s) exposure durations.

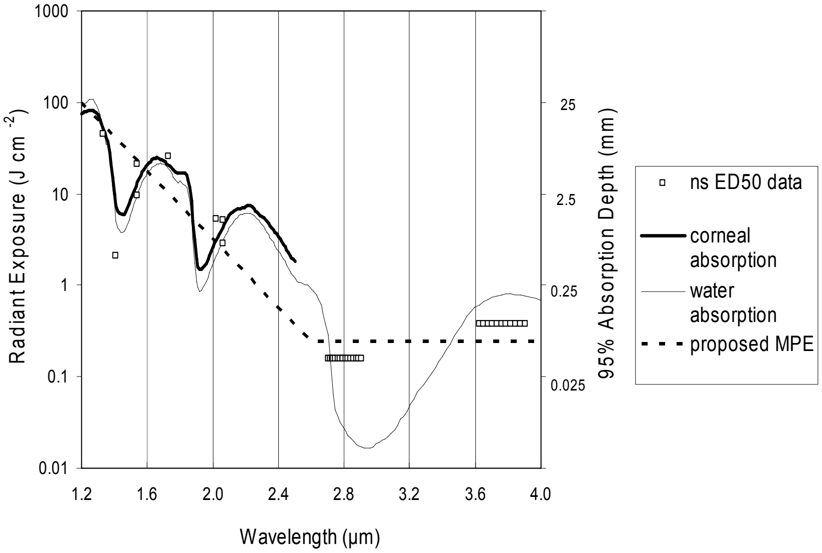

Figure 3. Corneal ED_{50} threshold data, and corneal and water penetration depths for 1.2 to 4.0 µm.

Figure 3 is a plot of corneal ED_{50} thresholds over the wavelength range from 1.2 to 4.0 µm (for ns pulsewidths). A horizontally elongated (rather than square) symbol indicates a corneal threshold determined with a laser source emitting multiple-IR wavelengths across the indicated range (e.g., ~3.6-3.9 µm for the symbol at the right-hand edge of the plot). The solid curves are plots of the corneal and water penetration depths (95% absorption depths, right-hand scale) as a function of wavelength. The data plotted in Figure 3, together with the corneal thresholds determined in recent studies [1-7, 12], suggest a proposed MPE that would generally follow the dashed lines included in the figure; i.e., a linearly decreasing function of wavelength from 1.2 to 2.6 µm, but levelling off to a constant value (horizontal dashed line) for longer wavelengths. Current MPEs are invariant with wavelength from 2.6 μm to 10^3 μm (for all exposure durations).

Proposal

Bearing the above discussion in mind, a proposal for revisions to the laser safety standard MPE levels has been formulated. No changes in MPEs are proposed for $\lambda \leq 1.2$ μm or $\lambda \geq 2.6$ μm. As suggested by the dashed lines of Figure 2, based upon the body of retinal ED_{50} threshold data and the wavelength dependence of ocular component absorption coefficients, it seems appropriate to extrapolate the wavelength-dependent MPE term found in the current laser safety standards (as defined for wavelengths from 1.15-1.20 μm and for all exposure durations) to wavelengths well beyond 1.20 μm. So, the proposed MPEs for wavelengths from 1.15 μm to some as yet unspecified upper limit, λ_c, will equal $c \times 10^{18(\lambda - 1.15)}$, where the proportionality constant, c, varies with exposure duration and λ is specified in μm. For any given exposure duration, t, the value of c is determined by equating the proposed MPE to the current MPE for that given value of t and for $\lambda = 1.2$ μm.

Above some upper limit of wavelength, absorption of the ocular medium becomes so great that there is no chance of inducing retinal damage and the definition of MPEs based on retinal damage ED_{50} levels becomes a mute point. For wavelengths beyond this point, corneal (and, in some instances lenticular) damage will be induced at incident exposure levels insufficient to result in retinal damage, and the MPEs should be defined in relation to corneal ED_{50} threshold data. Thus, the wavelength limit, λ_c, will designate the maximum wavelength where the MPEs are defined by the expressions derived from the trend of the retinal ED_{50} threshold data. Alternatively, λ_c, designates the minimum wavelength where the MPEs are defined in relation to corneal ED_{50} threshold data.

The proposed MPEs for wavelengths, $\lambda \leq \lambda_c \leq 2.6$ μm are derived by choosing MPE functions which follow the trends of corneal ED_{50} threshold data as exemplified by Figure 3. From Figure 3 it is seen that the wavelength dependence of the corneal ED_{50} data from ~1.2 μm to ~2.6 μm closely tracks the 95% penetration depth of the corneal incident radiation (which, in turn, for this wavelength range, closely follows the 95% penetration depth for water). Further, as indicated by the dashed lines in Figure 3, this relatively complex wavelength dependence is estimated, to a close approximation, by a best linear fit through the penetration depth and/or corneal ED_{50} threshold curves. Thus, the proposed MPEs for wavelengths from λ_c to 2.6 μm are chosen to be proportional to the corneal ED_{50}s as indicated by the dashed line of Figure 3, with the pulsewidth-dependent proportionality constant specified by equating the proposed MPE to the current MPE (for the same exposure duration) at $\lambda = 2.6$ μm.

The best fit equation derived from the corneal threshold data plotted in Figure 3 is:

$$\log (ED_{50}) = 4.240 - 1.867\lambda ,$$

and the proposed MPE which is chosen to be proportional to this expression for the corneal ED_{50} becomes:

$$\log (MPE) = 4.240 - 1.867\lambda - \log (m),$$

where, m, the safety margin between the proposed MPE and the experimental ED_{50} threshold is determined by requiring that the proposed MPE and the current MPE are equal at $\lambda = 2.6$ μm. For example, for the exposure duration range, $10^{-9} \leq t \leq 10^{-7}$ s, the current MPE is equal to 0.01 J cm^{-2} for $\lambda = 2.6$ μm. Equating the proposed MPE to 0.01 J cm^{-2} at $\lambda = 2.6$ μm, yields a value of m = 24.3, so the expression for the proposed MPE becomes:

$$\log (MPE) = 1.867 (1.529 - \lambda),$$

or, equivalently:

$$MPE = 10^{1.867 (1.529 - \lambda)}, \quad 10^{-9} \leq t \leq 10^{-7} \text{ s and } \lambda \leq \lambda_c \leq 2.6 \text{ μm}.$$

Likewise, the proposed MPEs for this wavelength range and other values of t are derived by equating the proposed and current values of MPE at $\lambda = 2.6$ µm. Completion of the proposal for revisions to the laser safety standard MPEs requires specification of λ_c, which also varies with exposure duration. Since a major objective of the proposed revisions to the IR MPEs is stated to be elimination of discontinuities in the MPE levels (both with wavelength and with exposure duration), λ_c is determined by requiring that, at $\lambda = \lambda_c$, the value of the proposed 'retinal' MPE for wavelengths $\leq \lambda_c$ is equal to the value of the 'corneal' MPE applicable to wavelengths $\geq \lambda_c$. In this way, λ_c has been calculated for values of exposure duration ranging from 10^{-9} s to 3×10^4 s and the results plotted in Figure 4. It is seen that λ_c varies from a value of ~1.45 µm for short exposure durations to a value of ~1.22 µm for exposure times greater than 100 s and varies as log (t) between these limits.

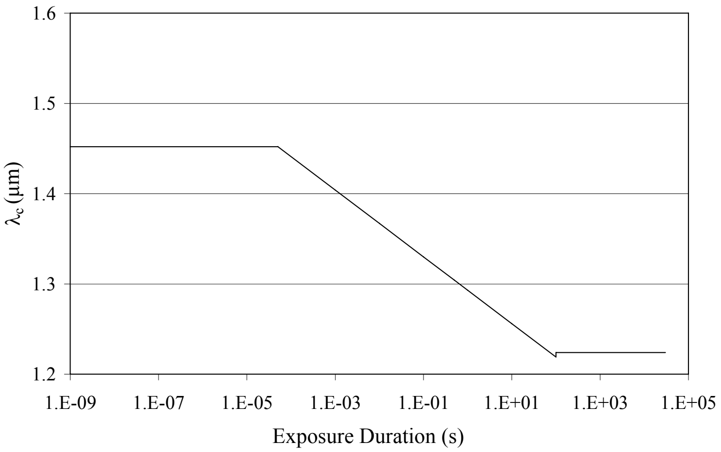

Figure 4. Plot of the parameter, λ_c, as a function of exposure duration.

The proposal for revisions to the safety standard IR MPE levels together with a comparison of the proposed MPEs to the current MPEs is summarized by the four sub-tables that comprise Table 2 and illustrated by the representative plots which follow. From Table 2, it is seen that for each combination of wavelength range and exposure duration range (the first two columns of each chart), the current MPE is either invariant over those ranges or follows the listed analytical functions of wavelength and/or pulsewidth. It is also seen that the transition from one wavelength range to the next often entails a discontinuity in the current MPEs. For example, for the pulsewidth range from 10^{-9} s to 50×10^{-6} s (Table 2.1), the current MPE is wavelength dependent: $5 \times 10^{18(\lambda - 1.15)} \times 10^{-6}$ J cm^{-2} for wavelengths from 1.15 to 1.2 µm but is invariant with a value of 40×10^{-6} J cm^{-2} for wavelengths from 1.2 to 1.4 µm before jumping to 0.1 J cm^{-2} for the range from 1.4 to 1.5 µm. The current MPE again jumps to 1.0 J cm^{-2} at 1.5 µm and finally reverses with a downward jump back to 0.1 J cm^{-2} at $\lambda = 1.8$ µm. The latter value then remains unchanged across the wavelength range of 1.8 to 2.6 µm. This behaviour is illustrated by Figure 1.

Contrast this behaviour of the current MPEs to that of the proposed MPEs (still looking at Table 2.1) which follow the same wavelength dependence ($5 \times 10^{18(\lambda - 1.15)} \times 10^{-6}$ J cm^{-2}), not just for the wavelength range from 1.15 to 1.2 µm but, based upon the experimental trend of retinal ED_{50} damage thresholds for short pulsewidths, is extrapolated across the wavelength range from 1.15 µm to $\lambda_c = 1.452$ µm. The step functions in the current MPEs which occur at 1.4, 1.5, 1.8 and 2.6 µm are eliminated by allowing the proposed MPEs to decrease with wavelength from ~1.39 J cm^{-2} at 1.452 µm to the value of the current MPE at 2.6 µm (either 0.01 J cm^{-2} for pulse durations from 10^{-9} to 10^{-7} s or $0.56t^{0.25}$ J cm^{-2} for pulse durations from 10^{-7} to 50×10^{-6} s). As argued in earlier reports [5-7] and illustrated by Figure 3, this wavelength dependence of the proposed MPEs for wavelengths $\geq \lambda_c$ is consistent with the observed trend of corneal damage thresholds. A plot contrasting the proposed MPE and current MPE over the wavelength range from 1.0 to 3.0 µm (for short pulsewidths) is seen in Figure 5.

Table 2. Current and proposed MPEs

Table 2.1. Exposure duration, $10^{-9} – 50 \times 10^{-6}$ s.

Wavelength (μm)	Exposure Duration (s)	Current MPE (J cm^{-2})	Proposed MPE (J cm^{-2})
1.05 – 1.15	$10^{-9} – 50 \times 10^{-6}$	5×10^{-6}	5×10^{-6}
1.15 – 1.20	$10^{-9} – 50 \times 10^{-6}$	$5 \times 10^{18(\lambda. - 1.15)} \times 10^{-6}$	
1.20 – 1.40	$10^{-9} – 50 \times 10^{-6}$	40×10^{-6}	
1.15 – λ_c	$10^{-9} – 50 \times 10^{-6}$		$5 \times 10^{18(\lambda. - 1.15)} \times 10^{-6}$
1.40 – 1.50	$10^{-9} – 50 \times 10^{-6}$	0.1	
1.50 – 1.80	$10^{-9} – 50 \times 10^{-6}$	1.0	
1.80 – 2.60	$10^{-9} – 50 \times 10^{-6}$	0.1	
2.60 - 10^3	$10^{-9} – 10^{-7}$	0.01	
2.60 - 10^3	$10^{-7} – 50 \times 10^{-6}$	$0.56\ t^{0.25}$	
λ_c – 2.60	$10^{-9} – 10^{-7}$		$10^{1.867(1.529 - \lambda)}$
λ_c – 2.60	$10^{-7} – 50 \times 10^{-6}$		$0.56t^{0.25} + 10^{1.867(1.529 - \lambda)} -0.01$

Table 2.2. Exposure duration, $50 \times 10^{-6} – 10$ s.

Wavelength (μm)	Exposure Duration (s)	Current MPE (J cm^{-2})	Proposed MPE (J cm^{-2})
1.05 – 1.15	$50 \times 10^{-6} – 10$	$9 \times t^{0.75} \times 10^{-3}$	$9 \times t^{0.75} \times 10^{-3}$
1.15 – 1.20	$50 \times 10^{-6} – 10$	$9 \times 10^{18(\lambda - 1.15)}\ t^{0.75} \times 10^{-3}$	
1.20 – 1.40	$50 \times 10^{-6} – 10$	$72\ t^{0.75} \times 10^{-3}$	
1.40 – 1.50	$50 \times 10^{-6} – 10^{-3}$	0.1	
1.40 – 1.50	$10^{-3} – 10$	$0.56\ t^{0.25}$	
1.15 – λ_c	$50 \times 10^{-6} – 10$		$9 \times 10^{18(\lambda - 1.15)}\ t^{0.75} \times 10^{-3}$
1.50 – 1.80	$50 \times 10^{-6} – 10$	1.0	
1.80 – 2.60	$50 \times 10^{-6} – 10^{-3}$	0.1	
1.80 – 2.60	$10^{-3} – 10$	$0.56\ t^{0.25}$	
λ_c – 2.6	$50 \times 10^{-6} – 10$		$0.56t^{0.25} + 10^{1.867(1.529 - \lambda)} -0.01$

Table 2.3. Exposure duration, 10 – 3 × 10^4 s.

Wavelength (μm)	Exposure Duration(s)	Current MPE (W cm^{-2})	Proposed MPE (W cm^{-2})
1.05 – 1.15	10 – 3 × 10^4	5×10^{-3}	5×10^{-3}
1.15 – 1.20	10 – 3 × 10^4	$5 \times 10^{18(\lambda. - 1.15)} \times 10^{-3}$	
1.20 – 1.40	10 – 3 × 10^4	40×10^{-3}	
1.40 – 1.50	10 – 3 × 10^4	0.1	
1.15 – λ_c	10 – 3 × 10^4		$5 \times 10^{18(\lambda. - 1.15)} \times 10^{-3}$
1.50– 2.60	10 – 3 × 10^4	0.1	
λ_c – 2.6	10 – 3 × 10^4		$0.1 + 10^{1.867(1.529 - \lambda)} -0.01$

Table 2.4. λ_c as a Function of Exposure Duration.

Exposure Duration (s)	Proposed λ_c (μm)
10^{-9} – 50 × 10^{-6}	1.452
50 × 10^{-6} – 100	1.293 – 0.037log(t)
100 – 3 × 10^4	1.224

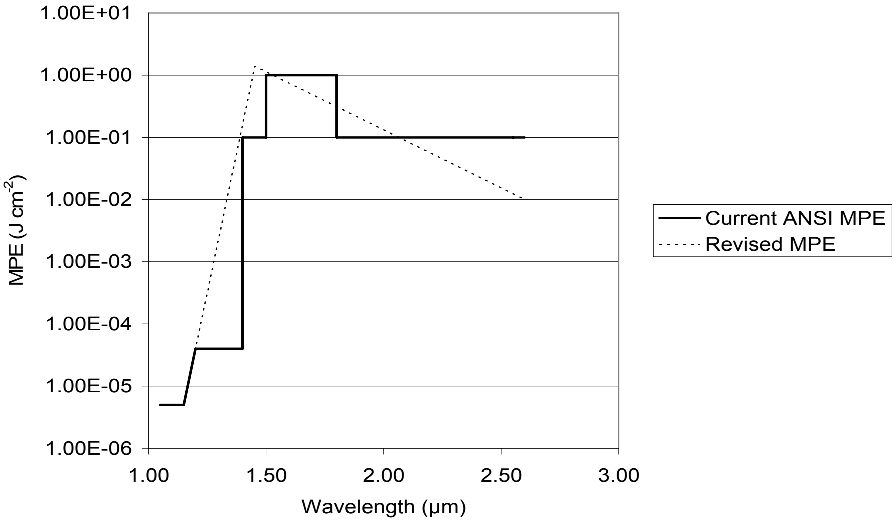

Figure 5. Current and proposed MPEs for exposure durations from 10^{-9} – 10^{-7} s.

Other step functions in the current MPEs (Tables 2.2 and 2.3) are eliminated in a similar manner; i.e., by proposing functions of wavelength that follow the general trends of retinal and corneal ED_{50} thresholds, and having these functions meet (without discontinuities) at a transition wavelength, λ_c. The transition wavelength, here, is defined as that IR wavelength below which the retina is the most sensitive ocular tissue and above which the cornea is more sensitive. The current laser safety standards do not address the transition wavelength issue in that, by default, the transition is assumed to occur at 1.4 µm for all exposure durations. Because the retinal and corneal thresholds vary so dramatically with wavelength, this leads to some instances of unusually large ED_{50}/MPE ratios such as seen in Table 1. The proposed MPEs track the retinal and corneal ED_{50} threshold trends more faithfully and, based upon the still limited threshold database, allow the transition wavelength to vary from 1.452 µm for short pulsewidths to 1.224 µm for longer pulses and cw exposures. Representative examples comparing the current and proposed MPEs for several exposure durations are seen in Figures 6-8.

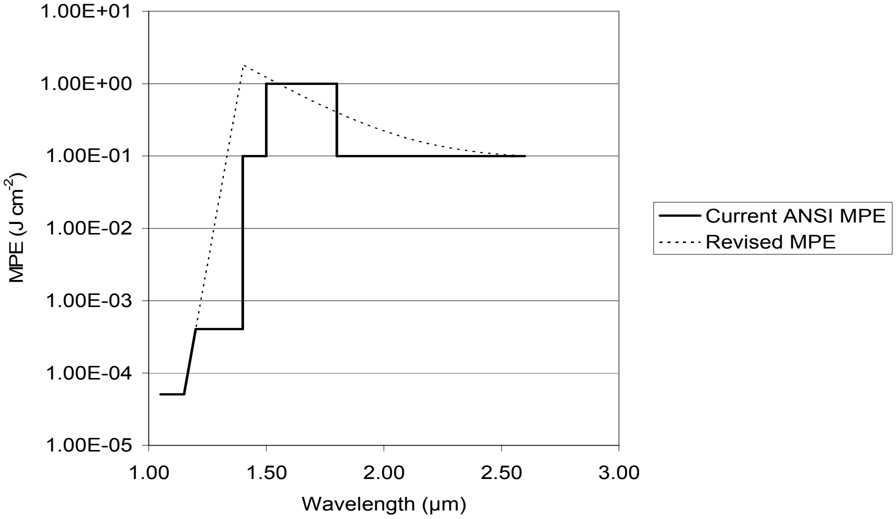

Figure 6. Current and proposed MPEs for 1-ms exposure duration.

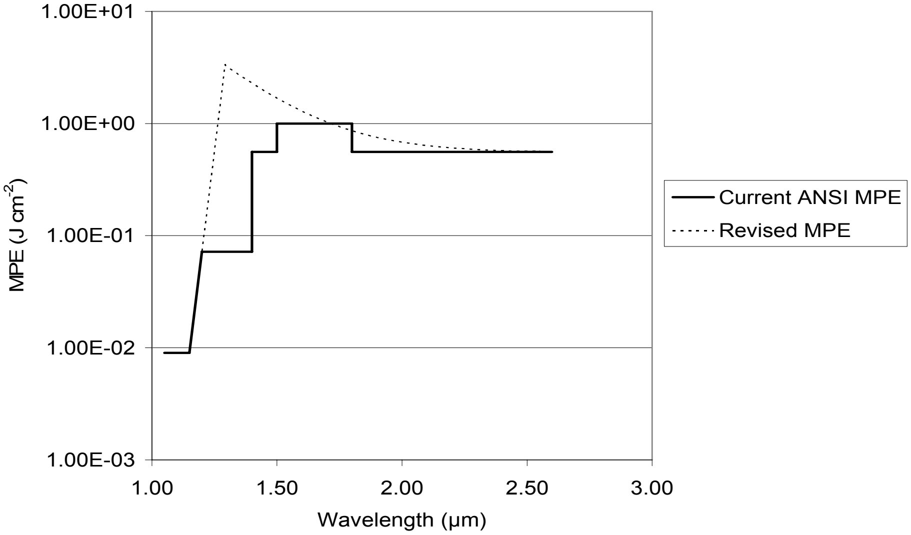

Figure 7. Current and proposed MPEs for 1-s exposure duration.

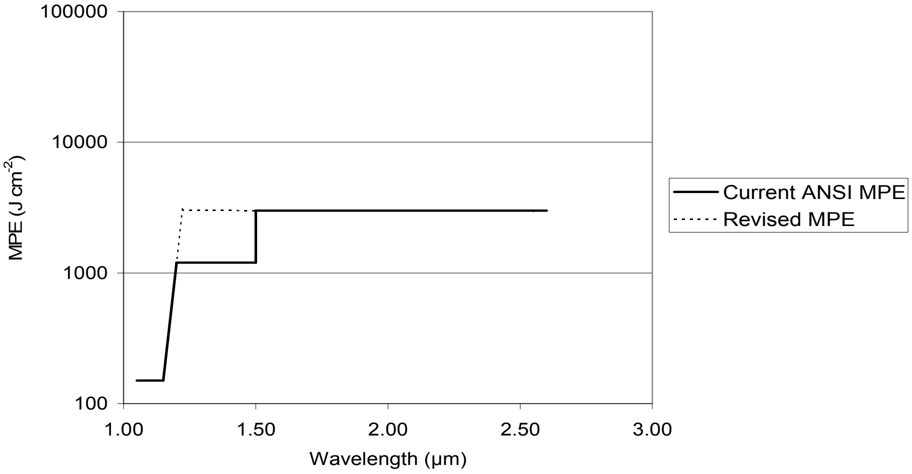

Figure 8. Current and proposed MPEs for 3 x 10^4 s exposure duration.

The proposed revisions to the safety standard MPEs thus appear to address the recognized shortcomings of the existing safety standards with regard to eliminating discontinuities in MPE levels while, at the same time, yielding MPEs which more faithfully track the observed trends of corneal and retinal damage thresholds. The consequences, on safety margins, of adopting the proposed MPE revisions (i.e., on the ED_{50} / MPE ratios) are demonstrated by Table 3. All published ED_{50} threshold data (both corneal and retinal ED_{50}s) for wavelengths from 1.15 to 2.60 µm are included in the table. In each case, the current MPE and the proposed MPE are tabulated, as are the ratios of ED_{50} to both current and proposed MPEs. It is seen that, for cases where the ratio of ED_{50} to current MPE is unreasonably large ($\geq 10^3$), the ED_{50} to proposed MPE ratio is much improved and lies closer (by a factor of ≥ 100) to the preferred safety margin of ~10. For almost every other case, the proposed MPE is generally close to the current MPE and either marginally improves the ED_{50}/MPE ratio (i.e., makes it closer to the generally accepted factor of ten) or leaves it unchanged.

Table 3. Comparisons of ED_{50} damage thresholds to current and proposed MPEs.

Reference	Wavelength (nm)	Pulsewidth (s)	Target Tissue	ED_{50} Dose (µJ)	Current MPE (J cm^{-2})	ED_{50}/MPE (current)	Proposed MPE (J cm^{-2})	ED_{50}/MPE (proposed)
11	1330	0.00065	retina	356000	2.93E-04	6500	0.064	14.4
5	1315	0.0003	retina	326000	1.60E-04	5200	0.019	44.6
5	1315	0.0003	retina	334000	1.60E-04	5200	0.019	45.7
5	1318	0.28	retina	~34E+06	2.80E-02	3150	2.87	30.7
5	1318	10	retina	>370E+06	4.00E-01	>2400	3.46	>275
7	1319	5.00E-08	retina	19300	4.00E-05	1250	0.0055	9.1
7	1319	5.00E-08	retina	22200	4.00E-05	1440	0.0055	10.5

Reference	Wavelength (nm)	Pulsewidth (s)	Target Tissue	ED$_{50}$ Dose (μJ)	Current MPE (J cm^{-2})	ED$_{50}$/MPE (current)	Proposed MPE (J cm^{-2})	ED$_{50}$/MPE (proposed)
5	1330	0.00025	cornea	1.07E+07	1.43E-04	3.15E+05	0.031	1450
15	1330	5	cornea	3.26E+06	0.24	880	3.18	66.5
5	1315	0.0003	cornea	390000	1.60E-04	2.60E+05	0.019	2200
1	1318	0.69	cornea	1.37E+06	0.055	3200	2.98	59
1	1318	0.28	cornea	560000	0.028	2560	2.87	24.7
5	1318	10	cornea	9.50E+06	0.4	4700	3.46	544
1	1356	0.22	cornea	224000	0.023	2500	2.48	23.2
1	1356	0.33	cornea	335000	0.031	2800	2.52	34.4
16	1410	2.50E-08	cornea	16400	0.1	21	0.239	8.79
11	1540	0.00093	cornea	75398	1	9.6	1.042	9.2
13	1540	5.00E-08	cornea	659734	1	10	0.954	10.5
12	1540	1.04	cornea	1.55E+05	1	70	1.51	46.2
12	1540	1.04	cornea	2.54E+05	1	32	1.51	21.3
12	1540	1.04	cornea	5.53E+05	1	15	1.51	9.94
12	1540	1.04	cornea	2.50E+06	1	13	1.51	8.6
12	1540	2.05	cornea	2.55E+05	1	120	1.61	74.5
12	1540	2.05	cornea	4.67E+05	1	60	1.61	37.7
12	1540	2.05	cornea	1.09E+06	1	29	1.61	18
12	1540	2.05	cornea	7.23E+06	1	19	1.61	11.8
12	1540	11	cornea	8.09E+05	1.1	330	2.04	162
12	1540	11	cornea	1.24E+06	1.1	140	2.04	68.6
12	1540	11	cornea	2.99E+06	1.1	72	2.04	35.3
12	1540	11	cornea	1.54E+07	1.1	40	2.04	19.6
12	1540	100	cornea	1.39E+07	10	37	10.9	33.9
12	1540	100	cornea	5.24E+07	10	16	10.9	14.7
14	1550	100	cornea	4.20E+05	10	1.56	10.9	1.43
17	1732	0.000225	cornea	61588	1	29	0.476	60.9
17	1732	0.000225	cornea	111822	1	26	0.476	55.6
17	1732	0.000225	cornea	146247	1	22	0.476	46
18	2020	0.082	cornea	36503	0.3	17.5	0.411	12.8
18	2020	0.235	cornea	58711	0.39	21.7	0.501	16.9
18	2020	4.28	cornea	341437	0.81	60.7	0.916	53.8
11	2060	0.0001	cornea	73796	0.1	29	0.148	19.5
11	2060	4.20E-08	cornea	4182	0.1	52	0.102	51
19	2500-3000	4.00E-09	cornea	3940	0.1	0.043	0.01	0.43
19	2500-3000	4.00E-09	cornea	12100	0.1	0.14	0.01	1.4

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