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COMPARISON OF COMPUTER MODEL THRESHOLDS WITH LASER SAFETY MPES FOR THE SKIN

Paper #P101

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Abstract

A computer model that predicts thresholds for laser induced skin injury was used to systematically analyze wavelength, pulse duration and beam diameter dependencies. The thresholds were compared with the respective maximum permissible exposure (MPE) values promulgated by ANSI Z136.1-2014, ICNIRP 2013 and IEC 60825-1:2014.

Due to discontinuities in the MPEs, the reduction factor between the predicted threshold and the MPEs varies widely. For some wavelengths, for beam diameters of 7 mm, the reduction factor is between 2 and 3 in the pulse regime of roughly 1 ms to 100 ms. For other wavelengths, the reduction factor is above 10.

The effect of the limiting aperture to reduce the radiant exposure is accounted for by increasing the MPE for beam diameters smaller than 3.5 mm. For small beam diameters, for the case that there is no relative movement between the beam and the skin (which has to be assumed for exposure to pulsed emission), this greatly reduces the margin between the predicted injury threshold and the MPE. Due to the averaging effect of the limiting aperture, for beam diameters of 1 mm, we found reduction factors considerably less than 1, particularly in the visible wavelength range, but also for wavelengths approaching 1400 nm. As a worst case, the MPE permits a factor 3 higher exposure levels than the predicted injury threshold. Since the reduction factors are particularly low in the regime between 1 ms and 100 ms, it is not possible to justify the 3.5 mm limiting aperture by relative movements of the laser beam and the skin. It is also questionable if scattering in the tissue is sufficient to generally justify the 3.5 mm limiting aperture. It appears prudent to consider an exposure-duration varying limiting aperture in the same way as for the cornea above 1400 nm, where for the pulsed regime the limiting aperture has a diameter of 1 mm.

Introduction

Exposure limits for laser radiation to protect the skin are promulgated on the international level by ICNIRP [1] and in the USA in ANSI Z136.1 [2]. Product safety emission limits for Class 1 are directly derived from the ICNIRP exposure limit values for the eye and are stated in the international laser product safety standard [3] IEC 60825-1. IEC 60825-1 in the Annex also features a copy of the skin exposure limits promulgated by ICNIRP. All of these limits are currently equal, including the circular limiting aperture with a diameter of 3.5 mm defined for averaging the exposure level to be compared against the skin MPE. This is to be accounted for by scaling of the MPEs as discussed in more detail further below.

In the thermal regime, i.e. for exposures where the injury mechanism is thermal and not photochemical as in the UV wavelength range, the wavelength and time dependence of the thresholds are related to the optical absorption and thermal diffusion properties of the target tissues. Contrary to the retinal thermal limits, the MPEs that apply to the skin do not feature a dependence on the diameter of the laser beam diameter that is incident on the tissue.

Thermally induced injury thresholds were calculated by means of a computer model. The computer model was validated against all applicable experimental injury thresholds for thermally induced injury of the skin as discussed by Jean and Schulmeister [4]. The endpoint for skin injury for the experimental data used to validate the computer model was the detection of a superficial redness or erythema by the naked eye. The skin model was validated against 288 experimental threshold values for exposure durations between 8 µs and 630 s, wavelengths between 488 nm and 10.6 µm, and beam diameters between 240 µm and 20 mm. For wavelengths less than 1600 nm the thermal model is assumed to be applicable for pulse durations equal to and larger than 100 µs in order to avoid non-thermal injury mechanisms of super-heated melanosomes, which are not part of the model. For wavelengths above 1600 nm, the thermal model is assumed to be applicable

for pulse durations down to 1 µs. The average deviation of the predicted threshold from the respective experimental threshold was 1.01, i.e. 1%. The maximum deviation of a single data point was 2.6 where the computer model predicted a threshold that was higher than the experimental data point, and a factor 2.4 where the computer model prediction was lower than the experimental data point, respectively. Overall, within this uncertainty band, considering the large experimental data set with varying wavelengths, pulse durations and beam diameters, the computer model should be a valid basis to characterize trends of the thresholds and a comparison with the respective MPEs.

In an ILSC 2019 paper [5], the trends for multiple pulses were shown for the example of a wavelength of 530 nm and 1320 nm for a pulse duration of 100 ms. In this paper, we present the comparison with MPEs in a more systematic way, as function of wavelength and exposure duration, with due consideration of the effect of the limiting aperture.

The Effect of the Limiting Aperture

For a safety assessment of skin exposure, the values of the MPEs are relevant, as well as, for small beam diameters or hot-spots, the averaging apertures that are defined for the determination of the irradiance or radiant exposure level. While the term used in the ANSI, IEC and ICNIRP document for these apertures is "limiting apertures", in terms of radiometric effect [6, 7] it is really an *averaging* aperture, since the irradiance and radiant exposure is averaged over the respective aperture. That is, the irradiance is determined by dividing the power that passes through the aperture by the area of the aperture. When the beam is smaller than the aperture, or when there are hot-spots smaller than the aperture, the averaged irradiance is smaller than the actual irradiance. Thus, due to the averaging aperture, the exposure level that is compared against the MPE is reduced compared to the actual irradiance at the skin. This is relevant for the comparison of the MPEs with injury thresholds, since when the *averaged* exposure level is equal to the MPE, the *actual* exposure of the skin (at least when there are no relative movements) can be higher than the MPE and thereby be closer to the injury threshold than the MPE value implies. When irradiance hot-spots or beam diameters are smaller than the aperture, the averaging aperture has the effect of reducing the margin between the exposure level permitted by the MPE and the injury threshold. For instance, if the beam profile on the skin is a top-hat with a diameter of 1 mm and the averaging aperture has a diameter of 3.5 mm, the actual irradiance is a factor of $3.5^2 = 12.3$ higher than the averaged radiance. The effect of the averaging aperture has to be accounted for in a comparison of injury thresholds with MPEs, in combination with relative movements. In some research papers on skin injury, the *thresholds* were corrected, considering this effect of the averaging aperture [8]. However, instead of decreasing the injury threshold by the respective factor, for the comparison with injury thresholds, we prefer to *increase the MPE* with that factor, such as for the example of a 1 mm beam, a factor of 12.3. We prefer this approach, since the experimental injury threshold is given by physical and biological properties that are not related or influenced by the averaging apertures defined in the standards. The averaging apertures are defined by ANSI or ICNIRP committees together with the MPEs, as rules for how to perform an MPE analysis. Thus, it appears more appropriate for a comparison of MPEs with injury thresholds, to leave the injury thresholds as experimentally or computationally determined (in our case with a stabilised beam and tissue, i.e. no relative movements), but increase the MPEs instead. The MPEs that - for beam diameters smaller than the limiting aperture - are increased with the ratio of the area of limiting aperture to the area of the beam are in this paper referred to as "scaled" MPEs. This scaling is only necessary for the comparison of biological thresholds with MPEs. For a workplace hazard analysis (being based on MPEs and not on injury thresholds), the MPEs would be used as defined and it is the exposure level that is "scaled" (averaged by the measurement aperture). The overall effect for both approaches is the same, namely decreasing the ratio between the injury threshold and the exposure level that is permitted by the MPE for the assumption of a stationary beam and a stationary target (which for 10 second exposure durations for normally behaving humans might be somewhat over-restrictive, but not impossible).

The ANSI and IEC standard defines a circular limiting aperture with a diameter of 3.5 mm for the determination of the exposure level to be compared against the skin MPE for wavelengths up to 100 µm. This is a constant diameter that also applies to short exposure durations - contrary to the limiting aperture defined for the eye in the wavelength range above 1400 nm, where the diameter equals 1 mm for exposure durations up to 0.35 seconds in the IEC standard and 0.3 seconds in the ANSI standard.

It should be noted the ICNIRP guidelines on exposure limits for laser radiation [1], for the case of laser beam diameters less than 1 mm, recommend that the *actual* radiant exposure is compared against the exposure limit and not the radiant exposure averaged over 3.5 mm (footnote b in Table 7).

When a certain extent of relative movement between the laser beam and the skin can be assumed for instance for a 10 second exposure duration, this will reduce the effective exposure level and would be associated to a higher injury threshold specified as irradiance in the beam. Since relative movements are not defined, it is difficult to account for that in a computer model. However, when relative movements are present, increasing the MPE with the ratio of the averaging aperture area to the beam area, as done in the analysis below, can be considered as "unfair", as it assumes a stationary beam and a stationary target. Therefore, for a more balanced discussion, more weight can be placed on the exposure duration of 1 second when the relative movements will be correspondingly smaller. As a conservative assumption, no relative movement can be assumed in the regime of 100 ms or shorter exposure durations (the term "exposure duration" will be used in this paper even when the term "pulse duration" might appear more appropriate for the regime of 100 ms and less).

Our computer model does not model scattering of the radiation in the tissue. We could predict experimental injury thresholds for beam diameters down to 0.7 mm for wavelengths of 1314 nm within the stated maximum deviation. The comparison between model and experimental thresholds plotted as function of beam diameter [4] shows that for beam diameters of 2 mm or less, the model prediction was for the majority of the data rather too high than too low. This indicates that scattering of the radiation in the tissue does not significantly increase the effective irradiance diameter. This is relevant since scattering is sometimes used to justify a 3.5 mm limiting aperture to be applicable also to pulses.

Model Results

General Issues

All predicted thresholds presented in this paper were obtained for a level of melanin pigmentation used to validate the computer model against experimental thresholds for the skin of the Yucatan miniature pig, which has a dark grey skin color.

The beam profile for the model was a circular constant irradiance profile with a given diameter. Such a profile is also referred to as top-hat. A top-hat profile facilitates comparison with the MPEs scaled for the effect of the limiting aperture.

Beam-diameter Dependence

Figure 1 plots the predicted injury thresholds as function of incident beam diameter for 10 second exposure duration, for four selected wavelengths. We see that the threshold for larger beam diameters is lower than the threshold for smaller beam diameters. This beam-diameter dependence is well known from retinal thermal injury thresholds [9,10] and is the basis for the dependence on α in the retinal thermal MPEs. Contrary to the retinal thermal MPEs, the skin MPEs are kept simple and do not feature a beam diameter dependence.

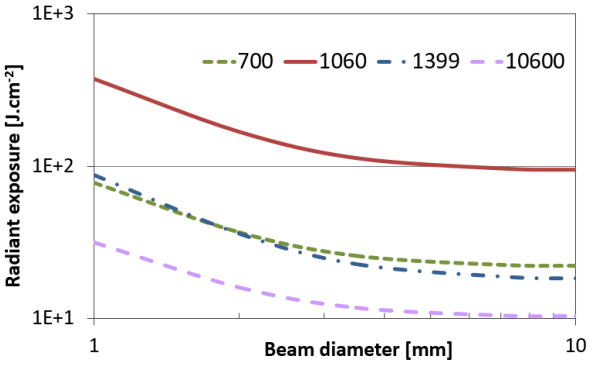

Figure 1. Predicted injury thresholds for 10 second exposure duration, as function of incident beam diameter, for a selection of wavelengths given in the legend in the units of nm.

Figure 2 shows the threshold/MPE ratio (referred to as reduction factor) where the MPE was scaled for beam diameters below 3.5 mm to account for the effect of the limiting aperture. The effect of the scaling with the inverse of the square of the beam diameter is to a degree compensated by the higher injury threshold for small beam diameters, so that when some relative movements of the laser beam and the skin are assumed for 10 s exposure duration, the reduction factor can probably be seen as sufficient.

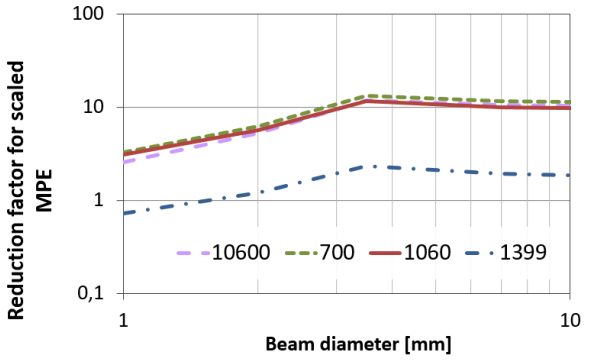

Figure 2. Reduction factor (factor between threshold and MPE) for an exposure duration of 10 seconds. Due to the scaling of the MPE, the reduction factor decreases for beam diameters smaller than 3.5 mm.

For short exposure durations there is no relevant heat flow during the exposure and consequently there is no relevant dependence of the injury threshold on beam diameter. Consequently, the scaling effect of the limiting aperture is not compensated, and the reduction factor falls below a factor of 1 (Figure 3 shows data for 10 ms exposure duration) for most wavelengths and beam diameters of 1 mm or less.

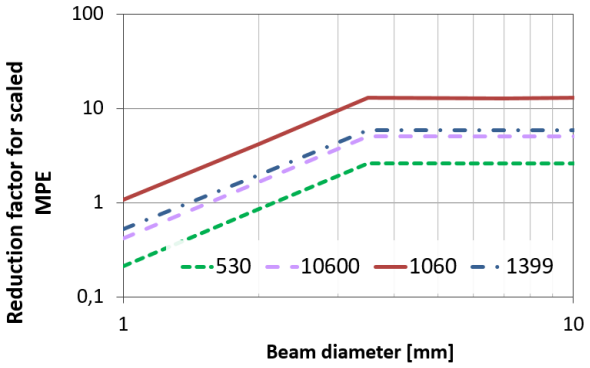

Figure 3. Reduction factor for an exposure duration of 10 ms.

We note in Figure 3 that with the exception of data for the wavelength of 1060 nm, a reduction factor of less than 1 is found for small beam diameters. The reduction factor for 530 nm is the lowest from the available data-set (400 nm would be associated to even lower reduction factors but was not available as function of beam diameter) and becomes less than 1 for beam diameters of about 2 mm. This means that for 1 mm beam diameter, the radiant exposure permitted by the MPE is higher than the predicted injury threshold, also when considering the uncertainty range of the model predictions. For exposure durations of 10 ms, one cannot argue with generally applicable relative movements reducing the effective exposure level.

Exposure Duration Dependence

Figure 4 shows the predicted injury thresholds as function of exposure duration between 100 µs and 10 s for a beam diameter equal to 1 mm. The curves for 530 nm and for 10.6 µm lie on top of each other and the curve for 530 nm is not shown. The curve for a wavelength of 400 nm is lowest in the collection, and associated to very small optical penetration depths. The regime of thermal confinement can be discerned when the thresholds assume a constant level for short exposure durations. Wavelengths that are associated to larger optical penetration depths reach the state of no exposure duration dependence (thermal confinement) already at longer pulse durations as compared to the curves for 400 nm, 530 nm and 10.6 µm.

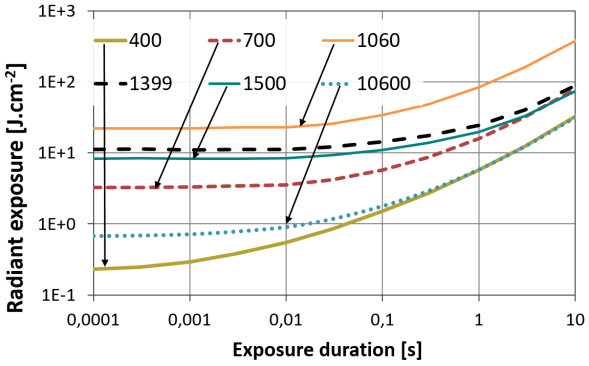

Figure 4. Predicted injury thresholds plotted as function of exposure duration, for a beam diameter equal to 1 mm.

Figure 5 shows the reduction factor for the thresholds plotted in Figure 4. The top figure shows the reduction factor without scaling of the MPE, i.e. without application of the limiting aperture to average radiant exposure. The lower figure shows the reduction factor for the case of a scaled MPE.

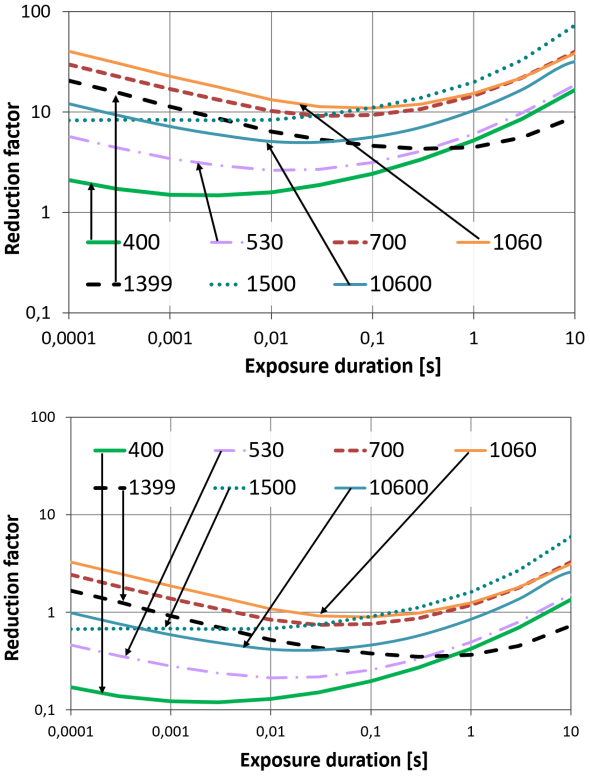

Figure 5. Reduction factor calculated for a beam diameter of 1 mm, plotted as function of exposure duration. The top plot assumes that the limiting aperture is not applied to average the radiant exposure. The lower plot accounts for the effect of the limiting aperture.

We note that for the case of 400 nm, the reduction factor without the application of the limiting aperture reaches a minimum of about 2 for pulse durations between approximately 100 µs and 10 ms, and for 530 nm a minimum of about 3 for regime between 1 ms and 100 ms. That is, even without the effect of the limiting aperture, the reduction factor is not "huge". Due to the limiting aperture, the reduction factor shown in the lower plot reduces to about 0.1 in this regime for 400 nm so that the averaged level permitted by the MPE is almost a factor of 10 above the predated injury threshold. For 530 nm, the MPE is a factor of about 3 above the predicted injury threshold.

Figure 6 shows the reduction factor for the case of the incident beam diameter being equal to 7 mm. In this case, the limiting aperture has no effect, so that the scaled MPE is equal to the unscaled MPE. A small reduction factor is found again for 400 nm of 1.5, but also for 530 nm and exposure durations in the regime of about 1 ms to 100 ms of 3 and less (the minimum equals 2.6). Other wavelengths feature higher reduction factors, such as a minimum of 5 for the wavelength of 10.6 µm, found for exposure durations between 10 ms and 100 ms. The wavelength of 1399 nm is associated to a reduction factor of about 2 for 1 second exposure duration. When injury thresholds are known with good accuracy (ideally somewhat better than the uncertainty associated to the computer model, and also accounting for different skin pigmentation types) a reduction factor of 2 can be seen as to be sufficient.

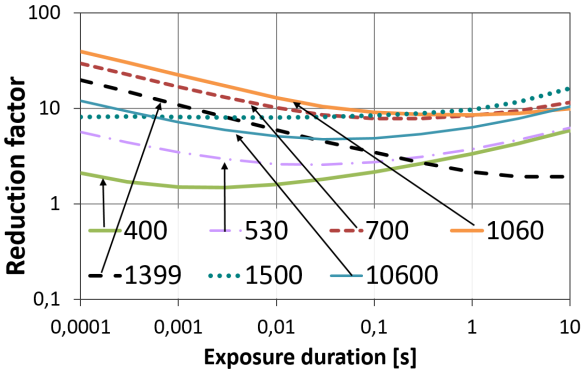

Figure 6. The calculated reduction factor for a beam diameter of 7 mm.

Wavelength Dependence

Figure 7 shows the predicted injury thresholds as function of wavelength, for a 7 mm beam diameter. Note from Figure 4 that for most wavelengths, the injury threshold does not become notably smaller for exposure durations less than 10 ms. Consequently, the exposure duration of 10 ms is representative also for shorter exposure durations. In Figure 7, the wavelength range of 400 nm to 2400 nm is plotted. This data is complemented by the injury threshold calculated for a wavelength of 10.6 µm to be equal to 0.8 J cm^{-2} for 10 ms, 3.5 J cm^{-2} for 1 s and 10.4 J cm^{-2} for 10 s, respectively. For 10 ms pulse duration, we see a pronounced wavelength dependence in the visible wavelength range, which is not reflected in the MPEs. We also note a pronounced wavelength dependence being predicted in the regime starting at about 1300 nm, where there is a local maximum, and a reduction to the minimum at about 1450 nm. Note that the skin MPE features a constant wavelength dependence between 1050 nm and 1400 nm where $C_A = 5$. At 1400 nm, there is a pronounced discontinuity in the MPEs.

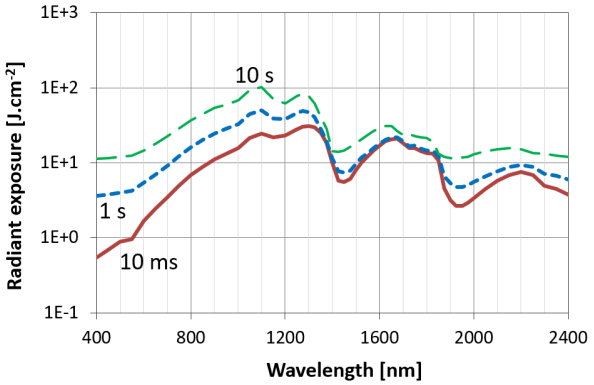

Figure 7. Predicted injury thresholds for 7 mm beam diameter as function of wavelength.

Figure 8 shows the reduction factor plotted for two different wavelength sections, for a beam diameter equal to 7 mm. We can see some strong variations in the reduction factors, which are due to discontinuities in the MPEs and simplifications of the MPEs with respect to wavelength dependence, for instance featuring a constant MPE in the visible wavelength range as well as from 1050 nm to 1400 nm. The smallest reduction factor is found for 10 ms exposure duration and a wavelength of 400 nm to be 1.6.

Note that the MPEs in the wavelength range above 1400 nm are derived from corneal injury thresholds, i.e. to protect the cornea, and are used for the skin in an equal way for simplicity (although the difference is that for the cornea, the limiting aperture in the pulsed regime has a diameter of 1 mm). The plot does not show the reduction factor for 10.6 µm, which equals 5.1 for 10 ms, 6.3 for 1 s and 10.4 for 10 s, respectively.

Overall, for a 7 mm beam diameter, the smallest reduction factor for exposure durations up to 10 seconds is found for 1399 nm with a factor of 1.5 for 10 s and 2.1 for 1 s exposure duration, respectively. Such a reduction factor can be considered as sufficiently large

provided that the injury threshold is known with sufficient accuracy, which is not really the case for the computer model used, because the true injury threshold might be somewhat lower as predicted.

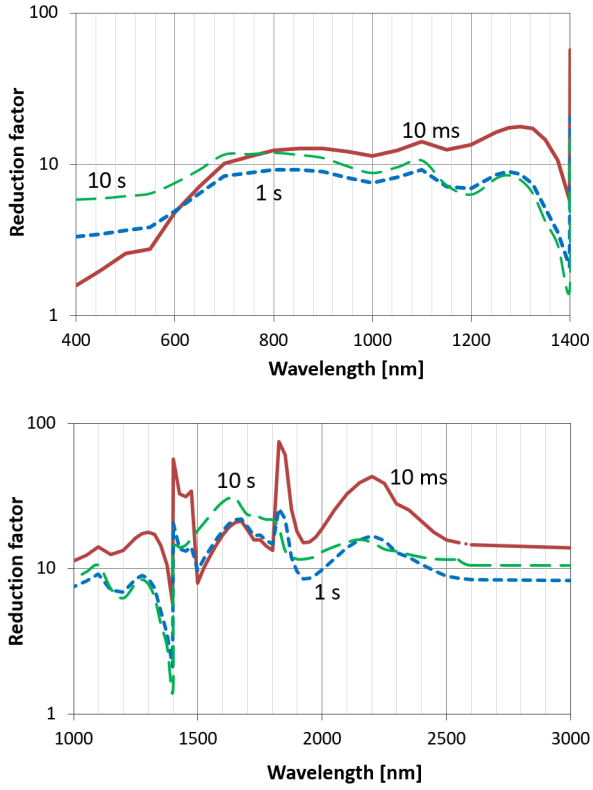

Figure 8. The reduction factor shown as function of wavelength for a beam diameter equal to 7 mm diameter.

Figure 9 shows the calculated reduction factors for a beam diameter of 1 mm, using scaled MPEs to consider the effect of the 3.5 mm limiting aperture. In the upper plot we can see that for the visible wavelength range, for 10 ms and 1 s exposure duration, the reduction factor is less than 1. The lowest reduction factor is found for 10 ms for a wavelength of 400 nm where the reduction factor equals 0.13. This means that the irradiance permitted by the MPE in combination with the 3.5 mm limiting aperture is a factor of more than 7 above the predicted injury threshold.

For 10 ms exposure duration and wavelengths between 800 nm and 1200 nm, the reduction factor is close to constant and equal to 1.

In the lower plot, for 10 ms exposure duration, we find a reduction of less than 1 for wavelengths approaching the step function at 1400 nm, and for wavelengths somewhat above the step function at 1500 nm. For 10 ms, for several other wavelength regimes, the reduction factor is close to a level of 1.

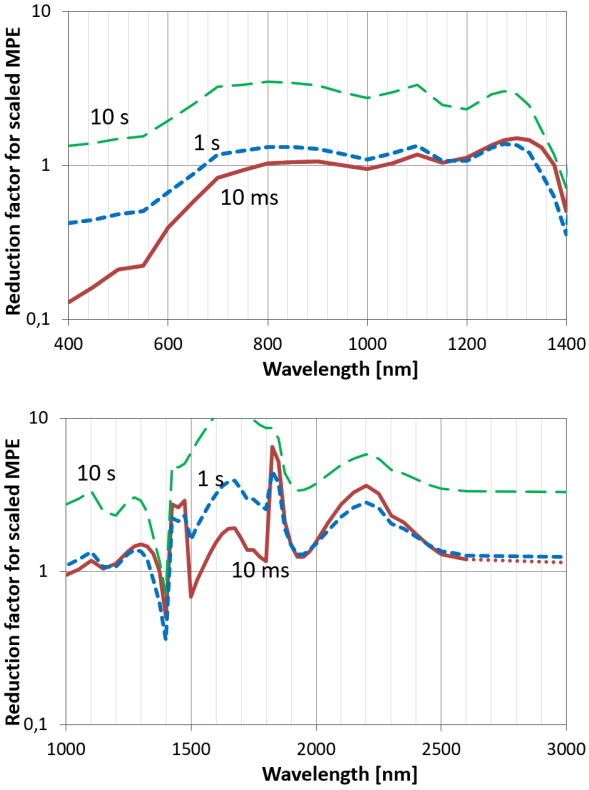

Figure 9. The reduction factor for the scaled MPE shown as function of wavelength for a beam diameter equal to 1 mm diameter.

Summary and Conclusions

Comparison of computer model thresholds for thermal injury of the skin with the skin MPEs show that for beam diameters of 3.5 mm and above, the reduction factor between the threshold and the MPE varies over almost two orders of magnitude but is never less than 1.5. This value of 1.5 is found for 1 ms to 10 ms exposure duration and a wavelength of 400 nm. While this minimum reduction factor is not “enormous”, it can be seen as sufficient.

The situation is different for beam diameters less than 3.5 mm. The 3.5 mm limiting aperture results in averaged radiant exposure levels which are significantly below the actual irradiance levels. When the actually permitted radiant exposure level is compared against the injury threshold, we found significant regimes of wavelengths where the MPE permits exceeding the

predicted threshold by a up to a factor 7 in the worst case. The low reduction factors are found for the visible wavelength range, wavelengths approaching 1400 nm and for wavelengths a little above 1500 nm, in the regime of 1 ms to 100 ms where relative movements of the laser beam vs. the tissue cannot be generally assumed.

It appears justified to consider defining an exposure-duration varying limiting aperture diameter in the same way as for the MPEs protecting the cornea for wavelengths above 1400 nm. For a potential amendment of the skin MPEs, the regime of above and below 1400 nm needs to be distinguished. The origin of the skin MPE above 1400 nm is really the MPE to protect the cornea. Thus, it is not surprising that the thresholds for the skin show different trends than the MPE. When the skin-cornea MPE is to be amended in this wavelength regime, the cornea takes precedence – unless of course the skin has a lower threshold than the cornea. Other than the issue of the limiting aperture, there does not seem to be a reason for amending the skin MPEs for wavelength above 1400 nm.

For the wavelength range of 400 nm to 1400 nm, there is more flexibility to amend the skin MPEs, because they are independent from the ocular MPEs. Although an amendment does not appear necessary and is not recommended in this paper, the variation of the reduction factor with wavelength and exposure duration shows that there is room for better following the trends of the injury threshold and achieve a somewhat more consistent reduction factor.

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