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Comparison of Cornea and Skin Multiple Pulse Injury Thresholds with Laser MPEs

Paper # P106

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Abstract

According to current ANSI Z136.1, IEC 60825-1 and ICNIRP guidelines, two exposure limit criteria apply for the cornea and skin: the single pulse limit and the average irradiance limit. The reduction factor C_P for repetitively pulsed exposures need only be applied to retinal thermal limits, not to limits to protect the skin and cornea from thermally induced injury. Since only a very limited amount of animal studies for multiple-pulse thresholds are available for the cornea and skin, we have used a computer model to systematically study the threshold trends for exposure to multiple pulses. For a number of representative wavelengths and irradiance diameters, and two pulse durations, injury thresholds as predicted by computer models were compared to the two exposure limit criteria as a function of duty cycle (i.e. repetition rate), number of pulses and as a function of exposure duration. The results support the current multiple-pulse criteria for the cornea and the skin, i.e. no additional reduction of the single pulse limit by C_P: for those repetition rates where the single pulse limit is the limiting criterion, the reduction of injury threshold compared to the single pulse is weak. For higher repetition rates, when the average irradiance limit is the limiting criterion the worst case is a cw exposure (duty cycle 100%) and reducing the duty cycle, i.e. pulsed exposure, leads to increased (less critical) thresholds.

Introduction

The maximum permissible exposures (MPEs) for the skin stated in IEC 60825-1:2014 [1], ANSI Z136.1-2014 [2] and the ICNIRP guidelines of 2013 [3] are identical, and so are the MPEs for the cornea for wavelengths above 1500 nm. Some differences exist for the limits to protect the cornea for wavelengths less than 1500 nm as discussed in more detail in another ILSC 2019 proceeding paper [4], [5]. Classification limits equivalent to MPEs apply in IEC 60825-1 for the classification of products by the manufacturer, and the discussion in this paper therefore also applies to classification of products.

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 MPEs reflect the optical absorption and thermal diffusion properties of the target tissues. Contrary to the retinal thermal limits, the MPEs that apply to the cornea and skin do not feature a dependence on the diameter of the laser beam diameter that is incident on the tissue. For an exposure assessment, the exposure level is compared against the MPE where for small beams it is relevant that limiting apertures are defined for the averaging of the exposure level. For the skin, the limiting aperture is generally defined as 3.5 mm while for the cornea, the limiting aperture depends on the exposure duration t (the same t that is used to determine the MPE(t)). The diameter of the limiting aperture for the cornea equals 1 mm for exposure durations less than 0.35 s and 3.5 mm for exposure durations above 10 seconds, with a 1.5 $t^{3/8}$ dependence in between. When the beam is smaller than the limiting aperture or when there are hot-spots, the irradiance averaged over the limiting aperture (which is the level compared against the MPE) is smaller than the actual irradiance in the beam or in the hot-spot. In other words, due the averaging effect of the limiting aperture, the MPE permits a higher actual exposure level as is defined by the MPE since only the averaged (smaller) irradiance level is compared against the MPE.

For repetitive exposures to pulses with a given pulse duration, the safety analysis needs to consider both the exposure duration domain of one pulse, i.e. using the MPE determined for the pulse duration, as well as the overall exposure duration to the pulse train. This reflects that the injury threshold does not solely depend on the duration of a single exposure, but also on the number of exposures and the repetition frequency of the delivery. In other words, only comparing the exposure level to the MPE for a single pulse is not sufficient because of the possible accumulation of heat within the targeted tissue from one exposure to the next one. On the other hand, comparing the exposure level to the MPE that is defined for the entire exposure duration (such as 10 seconds, and given either as total radiant exposure or average irradiance) only is not sufficient because the actual heat delivery rate and the peak power of individual pulses would be disregarded. Consequently two evaluation criteria are defined by ANSI, IEC and ICNIRP:

1) The exposure level (energy per pulse or radiant exposure per pulse) of any pulse shall not exceed the MPE for the corresponding pulse duration (often referred to as "single pulse" criterion)
2) The exposure level from any group of pulses delivered over a duration T shall not exceed the MPE for that exposure duration T (often referred to as "average irradiance" criterion; here also referred to as the 2nd criterion)

A third criterion is defined in ANSI, IEC and ICNIRP for the MPEs to protect the retina, often referred to as the "reduced pulse criterion". It is defined as an extension of the first criterion (the single pulse criterion) where the single pulse MPE is reduced by a correction factor C_P that depends on the number of pulses within a given exposure duration T. This third criterion, however, is not required for the skin MPEs nor for the MPEs to protect the cornea in the infrared wavelength range (and due to the dose nature of photochemical limits, it is generally not applicable for photochemical limits).

For the second criterion, the "average irradiance" criterion it is important to recognize that there are two equivalent quantitative methods of determining the exposure level and specifying the MPE: either as average irradiance (averaged over some exposure duration T) or as radiant exposure determined (summed up) for a given exposure duration T. For the understanding of these two equivalent ways to analyze the "average irradiance" criterion it is helpful to discuss a few basic terms. The MPEs in principle depend on the parameter with the symbol "*t*", which is called the "exposure duration". This parameter *t* has to be understood as basic time dependence of the MPE, where *t* is set equal to the pulse duration when the single pulse criterion is applied and *t* is set equal to the exposure duration (here given the symbol T) for the second criterion, the average irradiance criterion. The thermal skin and corneal MPE(*t*) are given as radiant exposure up to $t = 10$ s, from which onwards the MPEs are given as constant irradiance. For an MPE analysis that is based on an assumed (maximum) exposure duration of T=10 seconds, for the average irradiance criterion, the exposure level is the average irradiance, i.e. the irradiance averaged over 10 seconds. This average irradiance is compared against the MPE (expressed as irradiance) for the skin or the cornea defined for $t \geq 10$ s. For assumed exposure durations T less than 10 seconds, the MPEs are given in terms of radiant exposure. For that regime, an MPE analysis can be performed either by determining the exposure level as radiant exposure (the total radiant exposure added up over a duration of T), or by transforming the radiant-exposure-MPE (MPE_H) into an equivalent irradiance-MPE (MPE_E) that can then be compared against the exposure level expressed as irradiance that has been averaged over T. The transformation of the MPEs is performed via simple division by the exposure duration:

$$MPE_E\,(T) = MPE_H(T)\,/T$$

The two methods are mathematically equivalent because the exposure level expressed as averaged irradiance $E_{av}(T)$ (averaged over T) is equal to the radiant exposure H added up over T and divided by T:

$$E_{av}(T) = H(T)\,/\,T$$

We see that a comparison of H(T) as exposure level with MPE_H expressed as radiant exposure mathematically expressed as "$H(T) < MPE_H(T)$?" needs to be divided by T on both sides to express the same as irradiance (averaged irradiance): "$E_{av}(T) < MPE_E(T)$?"

For the present study it is advantageous to express the second multiple pulse criterion, which is often referred to as the average irradiance criterion, as a comparison of the radiant exposure within a given exposure duration (which can also be less than or larger than 10 seconds) against the MPE expressed as radiant exposure. For exposure durations above 10 seconds, the irradiance-MPE is transformed into a radiant-exposure-MPE by multiplication by T. The exposure level to be compared against the MPE is then the radiant exposure per pulse H_{pulse} multiplied with the number of pulses that are within T:

$$H(T) = H_{pulse} \cdot N(T)$$

The two multiple pulse criteria can be expressed by one general rule, which is also stated in IEC 60825-1 in the section on the time base to be used for classification of products: the accessible emission of a product shall be below the AEL(*t*) for all emission durations *t* up to the time base. For an exposure analysis (i.e. MPE analysis) this can be expressed as the generic requirement that the exposure level determined for an evaluation duration *t* has to be below the MPE(*t*) for all values of *t* up to the assumed maximum exposure duration T (as a general rule, also exposure durations less than the assumed exposure duration have to below the MPE). When the variation of *t* starts with setting *t* equal to the pulse duration, then this general rule covers the single pulse criterion on the short side of *t*, and averaging over 10 s on the long side of *t* covers the average irradiance criterion (if the maximum exposure duration for the MPE analysis is assumed to be 10 seconds, which is usually the case). For constant pulse trains (constant energy per pulse, constant pulse duration and constant repetition rate) and beam diameters larger than 3.5 mm for the case of the cornea (so that the limiting aperture does not play a role), it is clear that a variation of *t* between the pulse duration and the assumed (maximum) exposure duration T (typically 10 seconds) is not needed since for a constant pulse pattern, the time-averaged irradiance remains constant while the MPE expressed as irradiance decreases steadily with increasing *t* up to 10 s; thus t = 10 s is the worst case for the averaging irradiance criterion. An evaluation longer than $t = 10$ s is also not relevant in an MPE analysis, since the irradiance-MPE is constant and the exposure level expressed as average irradiance, averaged over *t* longer than 10 s, is either the same or is smaller than for 10 s (an averaged value can never increase when the averaging range is increased). We also see that the term "exposure duration" used by ANSI, IEC and ICNIRP for the parameter "*t*" in the MPE(*t*) can be somewhat confusing and misleading, because *t* can also be the pulse duration and for non-constant pulse trains, has to be varied to cover groups of pulses up to the assumed exposure duration and in that case t is shorter than the actual exposure duration (referred to as T here) used for the MPE analysis (T can be understood as "maximum" exposure duration *t*, and also exposure durations *t* shorter than T have to be "safe", i.e. the exposure determined for $t < T$ has to be below the respective MPE(*t*). A more generally applicable term that could be used for the dependence of the MPEs on *t* (as well as for the AEL(*t*)) would be for instance "evaluation duration" – the duration for which the radiant exposure is determined as well as the MPE, and this evaluation duration, as a general principle for non-constant pulse trains, has to be varied between the pulse duration and the maximum assumed exposure duration.

The purpose of this study is to systematically analyze the trend of the corneal and skin injury thresholds for exposure to constant pulse trains and to compare this trend against the two MPE criteria. The approach chosen in this study was to calculate injury threshold levels for a large set of laser parameters by means of computer models and to compare these values with the applicable MPEs considering the evaluation criteria mentioned above. The discussion above on the different ways to express and understand the two MPE criteria is relevant also for the threshold analysis because these rules define the permitted exposure level for the cornea and the skin which have to be below injury thresholds in order to be sufficiently protective. Since for a given set of exposure parameters (number of pulses, etc.) the associated injury threshold needs to be compared against both MPE criteria, it is important to understand how the two criteria can be compared against the injury threshold, as also further discussed below.

The MPEs for the cornea and skin are discussed in detail in another ILSC 2019 proceedings paper [4].

Materials and methods

Thermally induced injury thresholds (THR) were calculated by means of two computer models: one specifically designed to predict the injury threshold for the cornea and validated against all available experimental data [6] [7], and one specifically designed to predict the injury threshold for the skin [8]. The skin model was at this point validated against a subset of the available experimental data and ongoing optimization will be addressed in a future publication, however, the predicted injury thresholds are already sufficiently validated to be used for a trend analysis and has only a slightly higher uncertainty as compared to the cornea model.

All injury thresholds predicted by the computer model are based on validations against experimental thresholds (sometimes but not always determined with probit analysis) with the following endpoints (so that the computer model predictions can also be understood as to be associated to these endpoints): for the cornea, the detection by means of a slit lamp of a minimal visible lesion appearing as a greyish white spot in the cornea and for the skin the detection by the naked eye of a superficial redness or erythema. The cornea model was validated to predict thresholds for exposure durations between 1 ns and 1800 s, wavelengths between 1064 nm and 10.6 µm, and beam diameters between 100 µm and 10 mm. The results obtained on the basis of experiments performed on animal models can be assumed to be directly applicable to the human cornea without modification. Comparison of the 174 experimental thresholds available for the purpose of validation, with predictions of the computer model showed a with a maximum overestimation factor of 1.7 (see [7] for a more detailed discussion).

The skin model is currently validated to predict thresholds for exposure durations between 350 µs and 70 s, wavelengths between 500 nm and 10.6 µm, and beam diameters between 240 µm and 20 mm. It is assumed that the results obtained on the basis of experiments performed on animal models can be applied to the human skin without modification. Comparison of the 93 experimental thresholds used for the purpose of validation, with predictions of the computer model showed a with a maximum overestimation factor of 1.8. All predicted thresholds in the frame of this study were obtained for a "strong" melanin pigmentation, corresponding to the dark skin of the Yucatan miniature pig.

Both computer models were used to calculate thresholds for the combinations of laser parameters shown in Table 1.

Table 1. List of laser parameters used to calculate injury threshold levels for both skin and cornea

Parameter	Value	Comments
Wavelength [nm]	530#, 1320, 1500, 1920 and 10600	# skin only
Beam diameter (top hat) [mm]	0.5*, 1, 2, 3 and 4#	* cornea only, # skin only
Pulse duration [ms]	1 and 100	-
Number of pulses	1, 2, 5, 10, 20, 50, 100 and 200*	* 20% D.C. only
Duty cycle (d.c.) [%]	2, 5 and 20+	+ in addition to c.w. up to 10 s

The wavelengths were chosen to cover the widest range of absorption coefficients. The pulse durations, in conjunction with the number of pulses and duty cycles, were chosen to cover the thermal regime outside of thermal confinement with exposure durations up to 10 s. Finally, the beam diameters (top hat irradiance beam profiles) were limited to a maximum of 4 mm in this study, for technical reasons of computing time. It is noted that not all combinations of wavelength, diameter and pulse duration were investigated. Injury thresholds were calculated for all combinations of wavelength and diameter for the pulse duration of 100 ms but only some for the pulse duration of 1 ms (this pulse duration is less relevant because of thermal confinement).

The skin MPEs defined by ANSI Z136.1-2014, IEC 60825-1:2014 and ICNIRP 2013 were used not only for comparison with the skin injury thresholds but also for comparison with the corneal thresholds (however, considering the limiting aperture differently, as discussed further below). The skin MPE can be used also for the cornea, because in IEC and ICNIRP the skin MPEs are identical to the corneal MPEs for wavelengths above 1400 nm. For wavelengths less than 1400 nm, Table A.4 of IEC 60825-1:2014 recommends to apply the skin limits to protect the cornea from excessive exposure that might not be hazardous for the retina (see further discussion in [4]). Since ANSI Z136.1-2014 has dedicated corneal limits for wavelengths less than 1400 nm and also has corneal limits that deviate from the skin limits between 1400 nm to 1500 nm for exposure durations less than 10 seconds, the analysis in this paper does not apply to all the corneal limits of ANSI Z136.1-2014.

The injury threshold for each parameter set (wavelength, pulse duration, number of pulses, repetition rate and beam diameter) is calculated by the models as energy (i.e. the energy in the top hat profile) necessary to reach the injury threshold. Thus for the example of a pulse train consisting of 10 pulses, the calculated injury threshold is the combined energy of those 10 pulses that at the end of the 10th pulse is predicted to result in an injury. This calculated injury energy-threshold is transformed into a radiant exposure value by division by the area of the beam. The injury threshold $THR_{H\_total}(t)$ expressed as total radiant exposure for the exposure duration *t* can then be compared against the two MPE criteria. For this comparison it is necessary to assure that the threshold and the MPE has the same radiometric dimension and meaning. It is possible to compare the $THR_{H\_total}(t)$ with the second MPE criterion directly (see discussion above) when the MPE is expressed as radiant exposure, i.e. a comparison with $MPE_H(t)$. However, for the single-pulse MPE criterion, either the threshold $THR_{H\_total}(t)$ has to be transformed into a “single pulse” value or the single pulse MPE has to be transformed into an equivalent value expressed as total radiant exposure, associated to the exposure duration *t*. Both representations of the same data were used for the figures below.

The effect of the limiting aperture (that would in an exposure analysis scale the exposure level that is compared against the MPE) is *for the case of the cornea* applied to the MPE (see a more detailed discussion in [4]). Therefore, for the cornea, the MPE for the case of beam diameters less than the limiting aperture, is a “scaled” MPE that is higher than the MPE (i.e. closer to the injury threshold) as defined in the MPE tables, and due to the dependence of the aperture diameter on *t* also has a different exposure duration dependence than the underlying (unscaled) MPE. Such a comparison of the scaled MPE with the injury threshold is “fair” only for the case that that both the laser beam as well as the cornea is stationary. This is not reasonably foreseeable for a human who is not under anesthesia and this method of analysis is therefore over-restrictive at least for exposure durations longer than very roughly 1 s. The limiting aperture of 3.5 mm that is specified for the determination of exposure levels to be compared against skin-MPEs *has not been applied* in this study to scale the skin-MPEs. The skin-limiting aperture has a constant diameter of 3.5 mm (i.e. no time dependence) and thus when considered would scale all MPEs, for the example of a beam diameter of 1 mm on the skin, with a constant factor of for instance $3.5^2 \approx 12$. Again, for exposure durations of seconds, movements of the laser beam and/or the skin would result in relative movements which can be argued to be roughly equivalent to the effect of the limiting aperture. A more detailed discussion of the limiting aperture for the case of single pulses and exposure durations in the regime of less than about 1 s is not in the scope of this proceedings paper.

In the following Figures 1, 2 and 3 we compare calculated injury thresholds with the applicable MPEs (the scaled MPE for the case of the cornea and unscaled MPE for the case of the skin). The duty cycle d.c. (defined as the ratio of pulse duration to pulse period) is used instead of the repetition rate in units of Hz. As the main abscissa for the data analysis we have chosen the exposure duration which can vary from the pulse duration up to 100 s in our plots. The alternative representation as function of number of pulses is shown in one of the diagrams below in Figure 2.

The example of Figure 1 shows how the injury thresholds expressed in units of radiant exposure can be compared to *both MPEs criteria* in one plot, i.e. represented on the same scale. The data is plotted in terms of total radiant exposure as function of the exposure duration, starting with the exposure duration being equal to the pulse duration of 100 ms. The "average irradiance" MPE (criterion 2), expressed as total radiant exposure, can be plotted directly (the MPE is also expressed as radiant exposure in the MPE table for exposure durations up to 10 seconds). The calculated injury threshold as described above can also be plotted directly. The "single pulse" MPE which limits the radiant exposure per pulse, however, needs to be transformed into an equivalent "radiant exposure within the exposure duration" value. This is achieved by multiplying the single-pulse MPE (i.e. the MPE for t = 0.1 s) by the number of pulses N that occur for a given exposure duration. Thus the single-pulse MPE is expressed as a limitation of total radiant exposure value within a given exposure duration. This way the two MPE criteria can be plotted in one graph together with the injury thresholds and are in terms of "radiant exposure within a given exposure duration". Per plot, when both MPE criteria are shown, it is not possible to consider more than one repetition rate, as otherwise, for the transformation of the single-pulse MPE, there would be a different scaling factor between N and exposure duration for the different repetition rates and that cannot be plotted in a meaningful way one plot. In the examples shown in Figure 1 for the skin and a wavelength of 530 nm, the d.c. was 20% in the upper figure (2 Hz repetition rate) and 2% in the lower figure (0.2 Hz repetition rate), respectively. It can be seen that with a duty cycle of 20%, the MPE for "average irradiance" (criterion 2) is more restrictive than the MPE for "single pulse", while it is the opposite for a duty cycle of 2% (although in this case the two MPE criteria are relatively close). For the case of the higher duty cycle and repetition rate of 2 Hz we see that the injury threshold becomes equal to the single pulse MPE for exposure durations of about 10 seconds. However, this is not relevant because the exposure is limited to a much lower value by the "average irradiance" MPE, i.e. the second MPE criterion, where the respective ratio between predicted threshold and skin MPE (the "safety margin") is of the order of 10 for 10 seconds exposure duration.

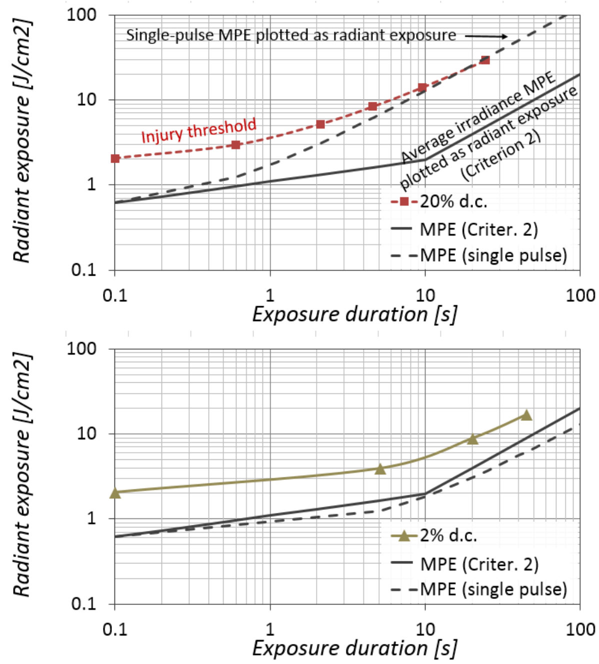

Figure 1. Comparison of both MPE criteria with the injury threshold for the skin (530 nm, pulse duration 100 ms, beam diameter 2 mm). Upper plot: 20% duty cycle (2 Hz); lower plot: 2% duty cycle (0.2 Hz)

As a general method, for each exposure duration (equivalent to the number of pulses), the ratio of the predicted injury threshold to the MPE is obtained for the more restrictive MPE criterion (i.e. the lower of the two MPEs, or in other words the MPE criterion that limits the exposure in an MPE analysis). This ratio is referred to as reduction factor (RF). In common terms this ratio is also often referred to as the "safety margin". The reduction factor for the more restrictive MPE criterion, as is further discussed and shown with the example of Figure 2 and Figure 3 in the bottom diagrams, was used as the primary figure of merit for evaluating the adequacy of the MPEs applicable to repetitively pulsed exposures. We see in Figure 1, where both MPE criteria are shown in one plot, that the more restrictive (i.e. the lower) MPE is associated to the larger reduction factor. Thus the relevant reduction factor is the larger one when comparing the reduction factor for the single-pulse and the "average irradiance" criterion (criterion 2).

In Figures 2 and 3, several duty cycles are shown within one diagram and therefore it is not possible to plot both MPE criteria together with the injury thresholds (Figure 2 for the cornea for a wavelength of 1320 and Figure 3 for the skin for a wavelength of 530 nm, also containing the data shown in Figure 1). The duty cycles span up to a range of 100%, which is the continuous wave (cw) case. Clearly this is no longer a train of pulses, but it is a valuable data set that is not only representative of very high duty cycles but is also the border of the cases studied.

The top diagrams shows the injury thresholds plotted as radiant exposure per pulse over the number of pulses. The single-pulse MPE is determined for the pulse duration of 100 ms and is a constant value in the top diagrams. As discussed above, the injury threshold that is the output of the computer model is the radiant exposure for the whole train of the pulse, so that the data plotted in the top plots is obtained by division of the "total radiant exposure threshold" by the number of pulses for a given exposure (this does not mean that each pulse contributes the same partial injury to the overall injury that occurs at the end of the last pulse; this transformation of the injury threshold is necessary in order to compare against the single-pulse MPE). The middle diagrams in Figure 2 and 3 show the injury thresholds as function of exposure duration, plotted as radiant exposure within the exposure duration. The injury threshold as such is the same as in the top plots, the data is just plotted in a different way in order to have a comparison with MPE criterion 2 (the average irradiance criterion, but here plotted as radiant exposure).

We see in the top plots of Figure 2 and Figure 3 that the threshold for the continuous wave (cw) exposure (i.e. a duty cycle of 100 %, representative of very high d.c.) approaches or is below the single pulse MPE. This is, however, not relevant because for this temporal exposure pattern (cw), the injury threshold when plotted as total radiant exposure is well above the second MPE criterion, i.e. the "average irradiance" criterion plotted in the middle diagrams – in fact the cw case is associated to the largest reduction factor when compared to the 2nd MPE criterion. The injury threshold for the smaller duty cycles (lower repetition rates) in the middle plots have a smaller reduction factor and for 2% d.c. approach the 2nd MPE criterion. However, for these small d.c., the single-pulse MPE is the limiting (restrictive) one and the reduction factor is correspondingly large as seen in the top plots.

Thus, as expected, depending on the repetition rate, it is either the single pulse MPE or the average irradiance MPE which is associated to the largest – and therefore the relevant – reduction factor. It is sufficient if one of the two criteria feature a sufficient reduction factor in order to conclude that the set of multiple pulse MPE rules are sufficiently protective and a reduction by C_P is not needed for the cornea or the skin.

In the bottom plots of Figure 2 and Figure 3 the information on the relevant reduction factor is combined by plotting, for each d.c. and exposure duration (number of pulses) the maximum reduction factor (maximum from the two MPE criteria). Thus the reduction factors for the low duty cycles result from the single-pulse MPE and the reduction factors for the cw case (representative for very high duty cycles) result from the average irradiance MPE (criterion 2).

It might be puzzling in Figure 2 that the time dependence of the "average irradiance" MPE (which is just the MPE as function of *t*) is different than found in the MPE tables. This is due to the effect of the time dependence of the limiting aperture which is used for the cornea to scale the MPEs when the beam diameter is smaller than the limiting aperture. This scaling effect, i.e. the increase of the MPE by the same factor that in an exposure analysis would reduce the actual irradiance, reduces the margin between the MPE and the injury threshold. As mentioned above for an exposure scenario where either the beam or the cornea or both are moving, the scaling of the MPE is "unfair" because due to the movement, the exposure level would actually be reduced and it would not be necessary in our analysis to increase the MPE (the scaled MPE reflects the scenario of a stationary beam and a stationary target tissue). Since the injury threshold is determined for a stationary beam and an anesthetized animal, and relative movement (for instance due to aversion responses to a temperature increase) is not standardised so that it could be considered in the computer model, we chose to scale the MPE but at the same we emphasize that the comparison of the scaled MPE with the stationary injury threshold is over-restrictive and "unfair". It is more realistic to place emphasis on the injury threshold for about 1 second exposure duration where little relative motion can be assumed but aversion response avoids longer stationary exposure. When the MPE were not scaled in Figure 2 (which is justified based on the assumption of movement for longer than roughly 1 s exposure duration), the reduction factor for the cw case would be higher by a factor of about 12 for 10 s exposure duration.

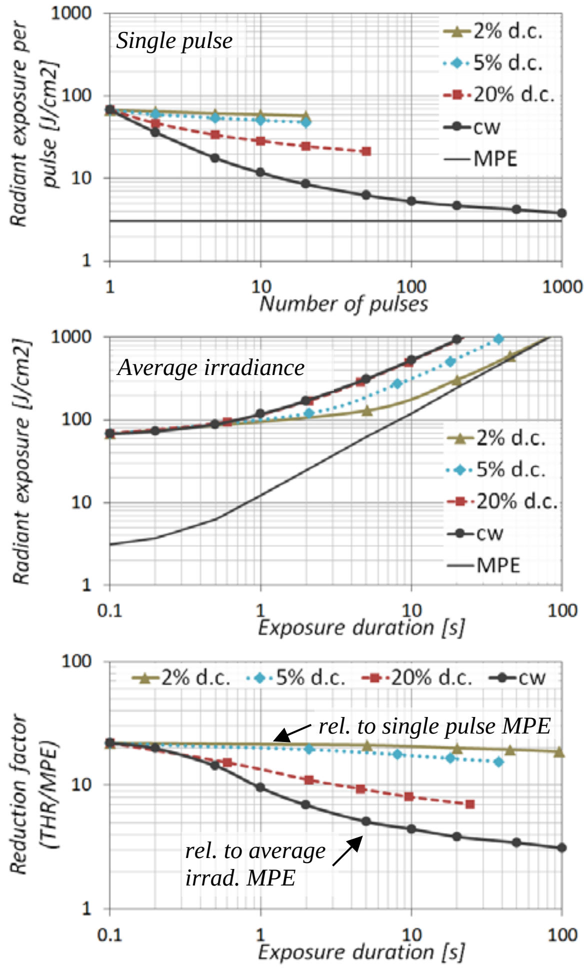

Figure 2. Comparison of injury threshold with MPEs for the cornea (1320 nm, pulse duration 100 ms, beam diameter 1 mm) according to the “single pulse” criterion (top) and the “average irradiance” - criterion 2 (middle). The bottom plot shows the maximum reduction factor obtained from both criteria.

Figure 3 shows an example for the skin and as noted above, the limiting aperture of 3.5 mm defined for the determination of the exposure level to be compared against skin MPEs was not specifically considered in this study (i.e. the skin MPEs, contrary to the corneal MPEs in Figure 2, were not “scaled”). If the limiting aperture were applied (which is “unfair”, at least for exposure durations of 1 s and above) then the reduction factor would be smaller for the case that the beam is smaller than 3.5 mm. This would apply to all MPEs in the same way, i.e. irrespective of number of pulses or exposure duration and is a simple shift applied to the MPEs.

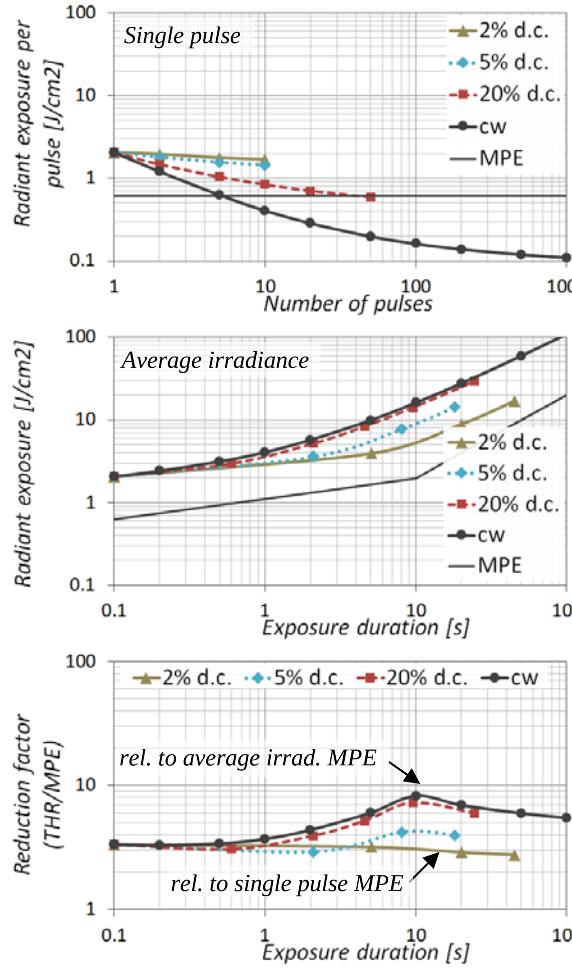

Figure 3. Comparison of injury threshold with MPEs for the skin (530 nm, pulse duration 100 ms, beam diameter 2 mm) according to the “single pulse” criterion (top) and the “average irradiance” - criterion 2 (middle). The bottom plot shows the maximum reduction factor obtained from both criteria.

For the example of the skin shown in Figure 3, the principle trends when plotted against the single pulse limit (top plot) and against the 2nd criterion (middle plot) is equivalent to the trends seen in Figure 2. However, in the bottom diagram with the maximum reduction factors per d.c. and per exposure duration, because the skin analysis is not associated with a time-dependent limiting aperture, the reduction factors for the high repetition rates (large d.c.) are larger than the reduction factors for low repetition rates (small d.c.). In this case, the lowest reduction factor is found based on the single pulse MPE. It can be seen (as is also the case for the cornea in Figure 2) that for low repetition rates where the single pulse MPE is the limiting one, the reduction of the injury threshold plotted as radiant exposure per pulse for multiple pulses is very weak. This means that the reduction factor (for low d.c.) is not strongly reduced with increasing number of pulses: the reduction factor for 2 % is a little bit above about 3 for one 100 ms pulses and it is a little bit below 3 for 50 second exposure duration. These types of low-repetition rate exposure patterns are therefore “covered” sufficiently by the single-pulse MPE. Again, higher repetition rates (in the extreme approaching d.c. = 100 %) are not “covered” by the single-pulse MPE (top diagram) but there is a correspondingly larger reduction factor based on the 2nd MPE criterion (the average irradiance criterion).

Results

With the methods discussed above, all injury thresholds obtained in this study were analyzed as a function of number of pulses for the “single pulse” criterion and as a function of exposure duration for the “average irradiance” criterion (the 2nd MPE criterion). For each set of exposure parameters, the two RFs (from the two multiple-pulse MPE criteria) were compared and the reduction factor for the critical criterion (the maximum reduction factor, as discussed for Figures 2 and Figures 3) was recorded.

For the laser parameters considered in this study, in most cases, the lowest RFs were obtained for the largest spots (3 mm for the cornea, 4 mm for the skin) and for the longest pulse duration investigated (100 ms as compared to 1 ms). This trend was, however, less obvious for the cornea than for the skin. Furthermore, the lowest RFs were in most cases obtained for durations towards 10 s and for low duty cycles, except for wavelengths associated with a relatively weak absorption coefficient (e.g. 1320 nm) where the cw exposure (large d.c.) was more restrictive than pulsed exposure of the same duration. The lowest RFs obtained in this study are summarized in Table 2.

The results show two general trends. Either the cw exposure (or close to 100% duty cycle) led to lower RFs than a pulsed exposure with a lower d.c. of same duration (such as in Figure 2) and in this case the “average irradiance” MPE criterion was the most restrictive criterion; or the pulsed exposure led to lower RFs than the cw exposure of the same duration (such as in Figure 3) and in this case the single-pulse MPE criterion was the most restrictive criterion.

As seen in Table 2, for the skin, for all wavelengths, the 4 mm beam diameter produced the lowest reduction factors. This result has to be seen together with the limiting aperture, which would be applied to an exposure analysis but was not applied in this present analysis. For the 4 mm beam diameter, that is the most restrictive one in this study, the limiting aperture does not play a role. However, for beam diameters of for instance 1 mm, for the case that relative movements or other reasons do not justify that the effect of the limiting aperture is not considered, smaller beam diameters might be more critical.

Table 2. Lowest reduction factors for both skin and cornea and for the different wavelengths

Wavelength [nm]	Lowest RF	Comments (beam diameter, pulse duration, duty cycle)
530 (skin)	2.7	4 mm, 100 ms, 2 pulses, 5%
1320 (skin)	2.9	4 mm, 5s (cw)
1500 (skin)	7.7	4 mm, 100 ms, 1 pulse
1920 (skin)	7.7	4 mm, 100 ms, 2 pulses, 5%
10600 (skin)	4.0	4 mm, 100 ms, 2 pulses, 5%
1320 (cornea)	4.4	1 mm, 10 s (cw)
1500 (cornea)	8.2	1 mm, 100 ms, 10 pulses, 20%
1920 (cornea)	7.6	2 mm, 100 ms, 5 pulses, 5%
10600 (cornea)	2.9	1 mm, 1 ms, 200 pulses, 2%

Discussion and Conclusions

To the knowledge of the authors, experimental work on injury thresholds for repetitively pulsed exposures is scarce. For the cornea, it is limited to lasers with wavelengths of 10.6 µm [9] [10], 2 µm [11] and 1.54 µm [12]. For the skin we can only identify a single study carried out with 1.54 µm lasers [13]. However, the underlying mechanism of thermally induced injuries can be modelled well with the Arrhenius integral and the abundant literature on single pulse or c.w. exposures allowed for the development of well validated computer models. These computer models are able to predict the increase in temperature in ocular and skin tissues and, in the absence of experimental results, are a valuable basis to investigate thoroughly the injury threshold levels for repetitively pulsed exposures.

The analysis of the selected set of injury thresholds for repetitively pulsed exposures and the comparison with the MPEs supports that the current multiple-pulse evaluation rules are adequate and sufficient for the cornea and the skin, and that no additional reduction factor C_P is needed. This conclusion is supported by the data for two the two main regimes. For the regime of high repetition rates, the most restrictive RF is obtained for cw exposure and the “average irradiance” or “cw” MPE is the limiting criterion. For this regime, a reduction factor does not need to be applied to the single pulse MPE because the single pulse MPE is not the relevant MPE (i.e. the potential hazard is “covered” by the average irradiance criterion). We note that for the case of large optical penetration depths and correspondingly long thermal confinement times, this regime is not only limited to high repetition rates but extends to low repetition rates. For the other regime, for repetition rates that are lower than a certain delineating rate, the injury thresholds when plotted as total radiant exposure or average irradiance would approach the average irradiance MPE, i.e. the 2nd MPE criterion, leading to a significantly lower RF as compared to the high-d.c. (or cw) case. However, when the injury threshold in this regime is plotted as radiant exposure per pulse, we see that the exposure is limited sufficiently by the single-pulse MPE. In this regime, the thresholds plotted as radiant exposure per pulse for increasing number of pulses is not significantly lower than compared to the single-pulse threshold. In other words, the reduction factor that is associated to the exposure to a single pulse is not significantly decreased for exposure to multiple pulses. Due to this very small "additivity" we see that the reduction factor C_P is not needed for the skin and cornea.

We note again that the goal of the study was not to determine whether the MPEs are adequate in terms of wavelength dependence or with respect to the application of limiting apertures, but to analyze the trend of the injury thresholds compared to the single pulse case and if it is justified not to apply a reduction factor C_P to the single-pulse MPE. Other issues of wavelength dependence or the applicability of limiting apertures, particularly for the skin, are not related to the trend of multiple pulse exposures and also, for instance, apply to the exposure of one single pulse.

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