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Karl Schulmeister and Mathieu Jean

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MODELLING OF LASER INDUCED INJURY OF THE CORNEA

Paper #903

Karl Schulmeister, Mathieu Jean

Seibersdorf Laboratories; Laser, LED and Lamp Safety Test House, 2444 Seibersdorf, Austria

Abstract

A computer model to calculate the injury threshold of the cornea of the eye following laser exposure was developed. The model is based on calculation of the laser induced temperature profile and subsequent integration with the Arrhenius integral. The model was validated against all available single pulse animal experiment threshold data for wavelengths between 1064 nm and 10,6 µm and pulse durations between 100 µs and 10 s.

Introduction

Laser radiation in the infrared wavelength range above 1400 nm is strongly absorbed in the anterior parts of the eye, i.e. mainly in the cornea. If the laser induced temperature rise in the cornea exceed a critical level, thermally induced injury occurs, which manifests itself in a clouding or whitening of the cornea. In the infrared wavelength range, absorption is governed by the water content in the tissue and experimentally determined injury thresholds for pulsed exposures (where heat flow has no effect) closely follow the wavelength dependence of the absorption depth of water [1].

Many studies on modelling of the laser induced injury of the retina using the Arrhenius integral were published since the 1970s (for instance [2,3]). To our knowledge, only Brownell and Stuck [4] applied the Arrhenius integral for thermally induced injury of the cornea, comparing model results with damage thresholds experimentally obtained with CO_2 laser radiation for different pulse durations. McCally [5] calculated a critical tissue temperature, which was also pulse duration dependent.

Here we describe a computer model for laser induced injury of the cornea that was validated against all available experimental single pulse damage threshold values.

Model Description and Validation

The heat flow equation is solved with a commercial finite element package COMSOL, the laser radiation being the energy source. The initial temperature is et to 34 °C in the vitreous and 22°C as boundary condition of the air 1 mm away from the tear layer. The absorption coefficient of the tissue as function of wavelength is taken from Boettner and Dankovic [6] and shown in Figure 1. Thermal properties are taken to be those of water, the Arrhenius parameters set to be equal to those that were used for the retinal injury model (see Paper #901 these proceedings). The cornea thickness was taken to be 500 µm which includes 7 µm of tear film. However, the tear layer is excluded from the region where damage is determined.

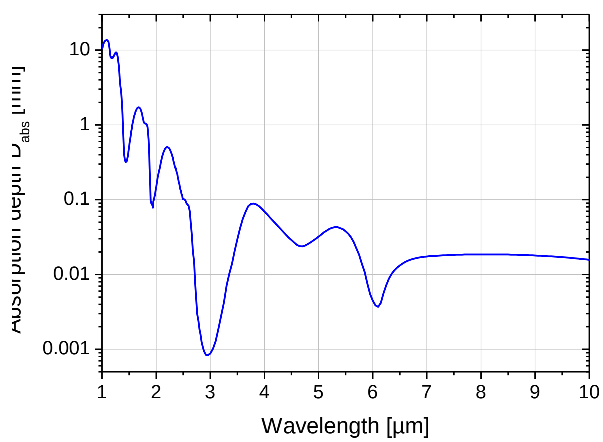

Figure 1. Absorption depth in corneal tissue (equivalent to the absorption depth in water) in the infrared wavelength range.

The predicted injury thresholds were compared to all available experimental injury thresholds determined for either rabbit or Rhesus monkey models [4, 7-16] which in terms of wavelength ranged from 1064 nm to 10.6 µm and in terms of pulse duration from 100 µs to 10 s. As shown in Figure 2, the computer model thresholds were not more than a factor 1.6 larger and not less than 0.6 smaller than the experimental threshold data.

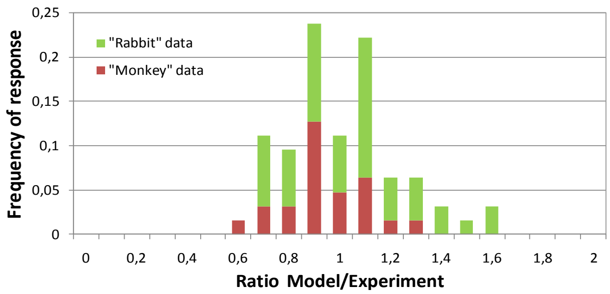

Figure. 2. Distribution of ratios of computer model to experimental threshold. Ratios are grouped into bins of 0.1.

An analysis of the differences of the computer model relative to the experimental data with respect to wavelength, pulse duration or spot size dependence did not reveal any systematic trends (which could be attempted to be corrected by varying the model parameters). Similarly, the average of the distribution of the rabbit and monkey data are not significantly different. This also indicates that deviation of the computer model from experimental thresholds is probably not a lack of the quality of the computer model but rather due to an inherent spread of the experimental data, due to differences in experimental techniques, endpoints, or biological variability.

Results

The computer model was used to calculate a collection of injury thresholds for a number of absorption depths that represent the absorption of optical radiation for wavelengths between 1050 nm and 10 µm, each for the range of pulse durations between 10 µs and 10 s and for a number of spot sizes.

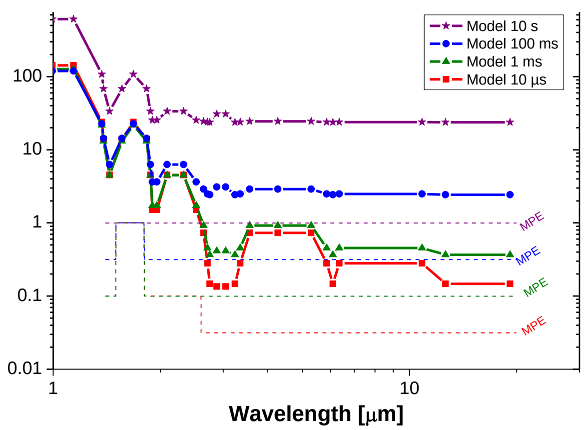

Figure 3. Corneal injury thresholds as calculated with the computer model for a spot size of 3 mm as function of wavelength.

The data for a 3 mm spot size, Gaussian beam profile is presented as function of wavelength in Figure 3 and as function of pulse duration in Figure 4. Exposure limits (MPE values) as given in ICNIRP [17], ANSI Z136.1 [18] and IEC 60825-1 [19] (all list equivalent thresholds) are also plotted.

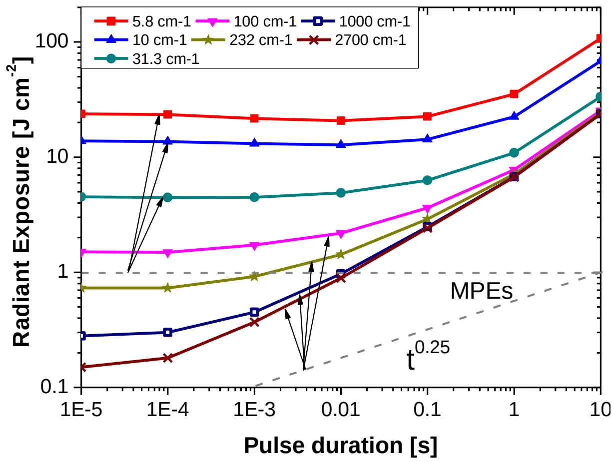

Figure 4. Corneal injury thresholds as calculated with the computer model for a spot size of 3 mm as function of pulse duration.

Discussion

It is interesting to note that the data from the computer model can predict injury thresholds in absolute terms with little uncertainty over a wide pulse duration und wavelength range (even for 1064 nm, which is very weakly absorbed in the cornea). This is remarkable, considering that we did not use any fitting parameter in the model; all the model parameters were taken from literature without amendment. Since we have used Arrhenius parameters previously derived for retinal thermal injury, and also validated by us against all available retinal injury thresholds, it can be inferred that the temperature tolerance or sensitivity for the cornea is similar to that of the retina.

The damage thresholds as calculated for 10 µs pulse durations and shown in Figure 3 closely follow the trend of the absorption depth as shown in Figure 2. For pulse durations in the thermal confinement time, heat flow does not play a role and the tissue temperature, for a given irradiance at the surface of the tissue is determined only by the absorption depth (a given amount of energy is available to heat a given volume). This dominance of absorption depth over thermal diffusion length still applies to the data in the wavelength range of 1000 nm to about 1800 nm (large penetration depth) for pulse durations up to 100 ms, so that damage thresholds for this wavelength range are similar for all pulse durations between 10 µs and 100 ms. In this regime the threshold curves lie on top of each other in Figure 3 (only the curve for 10 s deviates) and are seen as horizontal sections in Figure

4. The horizontal sections of no pulse duration dependence seen in Figure 4 are also referred to as to thermal confinement regime, since heat flow out of the heated volume (or centre of the volume) is negligible during the pulse duration. For this condition, the peak temperature at the end of the pulse only depends on radiant exposure, not on pulse duration. The shorter the penetration depth is, the shorter the thermal confinement time becomes.

For wavelengths where the radiation is absorbed strongly (such as at around 3 µm and for wavelengths above 5.5 µm), the optical penetration depths is very shallow and, especially for pulse durations of 100 ms and above, much smaller than the thermal diffusion length for this time domain. In this regime, where heat flow dominates over optical penetration depth the damage thresholds exhibit little or no wavelength dependence and are seen as horizontal sections in Figure 3 (such as for 10 s for wavelengths above about 2 µm) and in Figure 4 lie on top of each other (indicated by an ellipse).

The spot size dependence (no figure shown) exhibits equivalent trends as observed for the retina and discussed in detail elsewhere [20, 21]. Therefore, when there is delay of radial cooling of the centre of the irradiated corneal spot, larger spots exhibit a lower threshold value than smaller ones. This is because radial cooling reaches the centre of a smaller spot earlier and the temperature, for a given irradiance, is lower than for a larger spot.

A detailed comparison of the injury threshold data with the MPE values is not in the scope of this proceedings paper.

Conclusions and Summary

Thermally induced injury of the cornea can be modelled well by applying the Arrhenius integral and using absorption coefficient data from the literature. The maximum difference between the model and experimental threshold data is a factor of 1.7. The model can be used to study wavelength, pulse duration and spot size trends for comparison with MPE values or direct product safety analysis.

The injury model parameters (Arrhenius parameters) were the same as those used for modelling of retinal thermal injury, allowing the conclusion that the corneal cells have similar tolerance or sensitivity with respect to temperature increases as the retina.

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Meet the Authors

Karl Schulmeister, PhD, is a consultant on laser and broadband radiation safety at the Seibersdorf Laboratories, where also a specialized accredited test house is operated. Karl is a member of ICNIRP, the commission responsible for developing exposure limits for laser and broadband radiation on an international level. He is also the secretary of IEC TC 76 WG1, the working group responsible for IEC 60825-1. The research in his group over the last six years concentrated on thermally induced injury, providing the base for improving the spot size dependence of the retinal thermal exposure limits.

Mathieu Jean, MSc, is a PhD student registered at the Univ. Techn. Vienna, conducting his work at Seibersdorf Laboratories. He has optimized a retinal injury computer model and validated it against all available experimental injury thresholds, so that the model can be used for quantitative hazard and risk analysis of laser products (for instance scanned emission or irregular pulses). Mathieu also developed a computer model for laser induced injury of the cornea and the skin.