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COMPUTER MODELING OF LASER INDUCED INJURY OF THE SKIN

Paper #105

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Abstract

A computer model to calculate the injury threshold of the skin following laser exposure was developed. It is based on calculation of the laser induced temperature profile and subsequent integration with the Arrhenius integral. The model was optimized and validated against 93 experimentally determined threshold data (ED_{50}) in pigs and humans with various skin colors. The maximum deviation of the model w.r.t. experimental data is 1.9, which is small considering that the model was validated for a wide range of exposures encompassing wavelengths between 500 nm and 10.6 µm, exposure durations between 350 µs and 70 s and spot sizes between 240 µm and 20 mm. Finally, model predictions for heavily pigmented human skin are compared to current exposure limits.

Introduction

Laser radiation in the visible wavelength range is absorbed by the skin due to the melanin content in the epidermis and the water and fat content in the epidermis/dermis and subcutis, respectively for the infrared wavelength range. If the laser-induced temperature rise in the skin exceeds a critical level (that depends on the duration of elevated temperature), thermally induced injury occurs. A threshold lesion is commonly defined as a visually assessed superficial redness (erythema) without blister, which corresponds to a first degree burn (see also Paper by Bruce Stuck et al. in these proceedings). Depending on the assessment delay after exposure – 10 minutes to 48 hours – the injury description can be further refined, ranging from "instant redness" (e.g. [1]) to "mild erythema" (e.g. [2]).

In previously published models, the results were set against a narrow set of ED_{50}s at one or two specific wavelengths in the IR-A and IR-B ranges (see [3, 4]). These models provide useful numerical values for constant parameters such as skin layers thickness or thermal properties. However, the lack of wavelength-dependent parameters such as surface reflection or absorption coefficients requires further work.

Here we present an optimized computer model, similar in its approach to the abovementioned ones, applicable to a wide range of exposure conditions regarding spot size, exposure duration (including multiple pulses), wavelength of radiation and pigmentation (including lightly and strongly pigmented humans). This model was optimized in order to fit all available thermally-induced threshold injury data and validated so that it can be used for quantitative risk analysis.

Model description

The modeling of thermally-induced lesions requires at least three sub-models: an optical model providing the distribution of light absorption within the skin layers; solving of the bio-heat equation; and a damage model for predicting injury levels.

The geometrical model setup consists of three absorbing layers (epidermis, dermis and subcutis) in which three absorbers at various concentrations are considered (melanin, water and fat). Absorption coefficients are taken from the literature (from [5], [6, 7] and [8], respectively). The melanin data have been fitted and then optimized for the modeling of threshold lesions of the retina (see also Paper by Jean et al. in these proceedings). Light attenuation is assumed to be governed by the Beer-Lambert's law. Scattering is not modeled. Thicknesses have been adjusted in conjunction with absorbers concentration and thermal properties. At the skin surface, light is partly reflected. The amount of reflection is pigmentation- and wavelength-dependent. For lightly and strongly pigmented skins, we use the measurements from Rockwell and Goldman referred to as "light Caucasian" and "light Negro", respectively [9].

The bio-heat equation is solved numerically with a finite element software package (Comsol 3.5a, Comsol AB, Stockholm, Sweden, 2008). The initial temperature is set to 34°C at the deep end of the

subcutis while air temperature is set to 22°C. Tissue density, specific heat and heat conduction are temperature-independent (identical in all layers). Dermal blood flow is simulated by global heat sink [10] and set to 0 as a result of the optimization procedure. At the skin-air boundary, heat transfer consists of free convection (Newton's cooling law) and water evaporation (arbitrary function). Radiative losses are negligible in the temperature range relevant to threshold thermal lesions. The evaporative heat flux density writes:

$$Q_{evap} = -2(T-T_{air})^2$$

This arbitrary function is very similar to the models proposed by Chen et al. [3] and Wilson and Spence [11] up to 80°C. In our model, heat loss is dominated by water evaporation at temperatures above 30°C.

The determination of the injury level is achieved by using the commonly applied Arrhenius model, in which the weighted time-temperature history integrated over time gives a good measure of the observed macroscopic damage. Threshold is reached when the integral value gives 1. The adjusted values of *A* and *E* applied here are consistent with the time-temperature relationships for thermal damage found in earlier skin models and experiments (see Figure. 1).

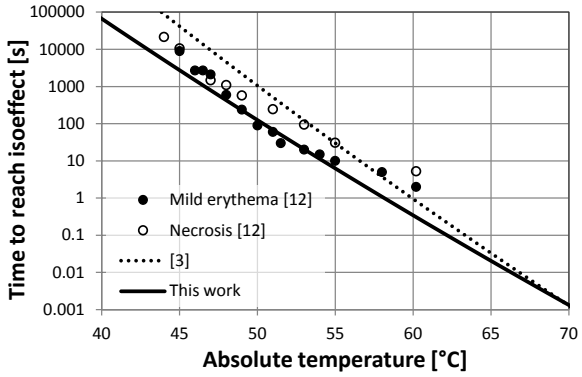

Figure. 1. Time-temperature relation to achieve thermal damage to skin

As shown histologically, threshold lesions are mostly confined around the interface between epidermis and dermis and are correlated with gross observations [13]. The damage model is thus applied to both epidermis and dermis, the computer model "searching" for the exact depth at which damage first occurs. A constant MVL diameter of 700 μm is found to be optimal in this model. This value is consistent with a typical threshold injury as shown in [14], for instance. Parameters of the thermal and damage models are tabulated in Table. 1.

	Value	*Unit*
Epidermis		
Thickness	100	μm
Melanin concentration (light)	7	%
Melanin concentration (strong)	15	%
Water concentration	30	%
Dermis		
Thickness	1000	μm
Water concentration	80	%
Fat concentration	20	%
Subcutis		
Thickness	2500	μm
Fat concentration	100	%
Thermal properties		
Specific heat	3400	$J.(kg.K)^{-1}$
Density	1100	$kg.m^{-3}$
Conduction	0.4	K
Heat transfer coefficient	15	$W.m^{-2}.K^{-1}$
Damage model		
Lesion diameter (MVL)	700	μm
pre-exponential factor (A)	1.75×10^{83}	s^{-1}
inactivation energy (E)	63000	K

Table. 1. Model parameters (see text for further details and additional values)

Model validation

In the literature we found 93 applicable in-vivo threshold data determined for various exposure conditions regarding wavelength (500 nm to 10.6 μm), spot size (240 μm to 20 mm), exposure duration (350 μs to 70 s) and pulse repetition rate (0.1 Hz). Lesion readings were performed between 10 minutes and 48 hours after exposure. The in-vivo models were Yorkshire, White, Handford (lightly pigmented), Yucatan (strongly pigmented) porcine flanks and lightly/strongly pigmented human forearms. References are [1, 2, 4, 9, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22] (see also Paper by Bruce Stuck et al. in these proceedings). Data given at ≤1h- and 24/48h-readings were pooled together since the average ratio is 1.08 (18 data couples).

Exposures for which the pulse duration was shorter than 100 μs or the lesion endpoint was no first-burn degree, or the assessment delay was longer than 48 hours, or the in-vivo model was not human or pig were not considered in this work for the sake of consistency. Besides these criteria, two 70-ms ED_{50}s at 1h and 24h were excluded [4] since they obviously depart from the expected pulse duration trend (see Figure. 2).

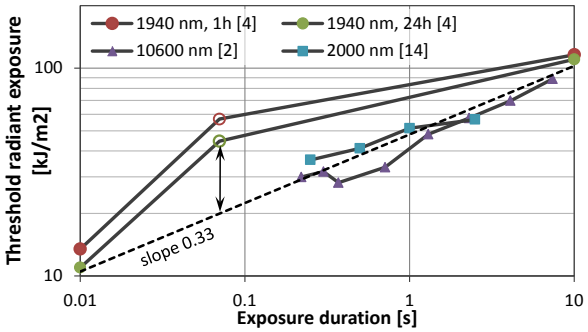

Figure. 2. Demonstration of two inconsistent large-spot threshold data (open circles) excluded from the model validation described in this work

The figure of merit used for model validation was the predicted injury thresholds to ED_{50} ratio (R_{ED50}). The computer model thresholds were not more than a factor 1.84 larger and not less than 0.52 smaller than the experimental threshold data (see Figure. 3). Noticeably, all ED_{50}s that were overestimated by more than 30% concern 1540-nm exposures [17, 20]. ED_{50}s for spots smaller than 1 mm in diameter (8 samples, down to 240 µm) can be reasonably predicted only by assuming a minimum spot size of 1 mm. This value was optimized in combination with the MVL diameter.

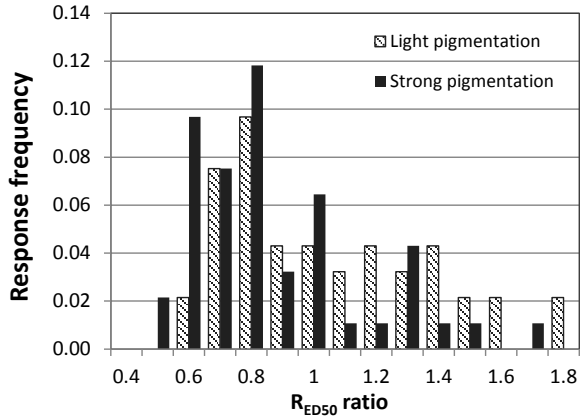

Figure. 3. Frequency response of model threshold to ED_{50} ratios for two different in-vivo and computer models (grouped into bins, constant bin size: 0.1)

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 when 1540-nm exposures are excluded (which could be attempted to be corrected by varying the model parameters). At the 0.01 level, mean of R_{ED50} is significantly different between the strong pigmentation model (0.84, 47 samples) and the light pigmentation model (1.0, 46 samples). The standard deviation (SD) for both groups is not significantly different (34% and 36%, respectively). Between the modeling of ≤1h- and 24/48h-ED_{50}s there is no statistical significance regarding both mean and SD.

Results

The computer model was used to calculate a collection of injury thresholds for strongly pigmented human skin at various wavelengths and pulse durations. The data for a 3 mm spot size, Gaussian beam profile is presented as function of wavelength in Figure. 4 and as function of pulse duration in Figure. 5. Exposure limits (MPE values) as given in [23, 24, 25] (all list equivalent values) are also plotted. The spot size was chosen as a worst case value to predict conservative values.

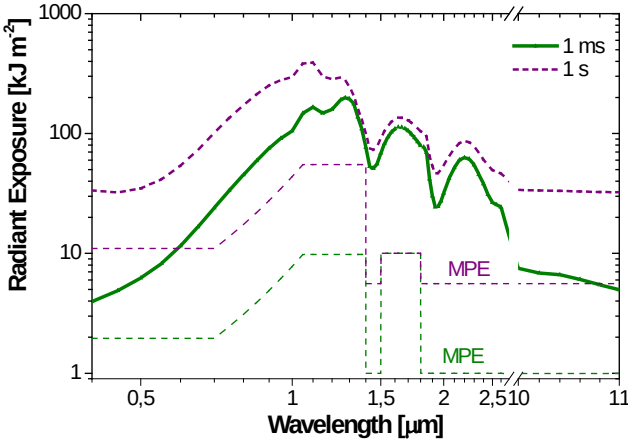

Figure. 4. Skin injury thresholds as calculated with the computer model for a spot size of 3 mm as function of wavelength

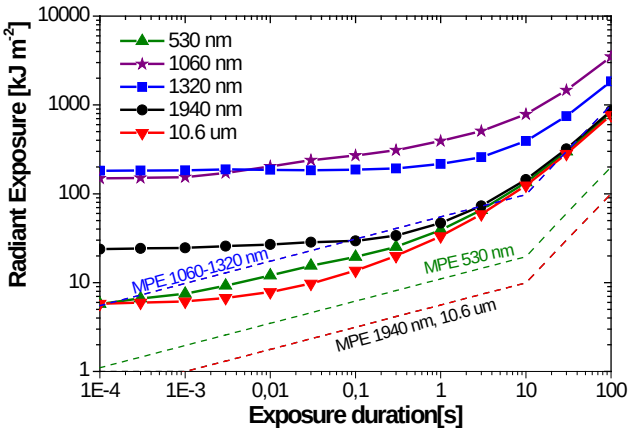

Figure. 5. Skin injury thresholds as calculated with the computer model for a spot size of 3 mm as function of pulse duration

Discussion

Model Optimization and Parameters

We would like to note that the computer model can predict injury thresholds in absolute terms with relative little uncertainty over a wide range of exposure conditions, in both porcine and human subjects). The high level of agreement was achieved by adjustment of mainly but not only: absorber concentrations, layer thicknesses and thermal properties. Precise modeling of heat transfer between skin and air turned out not to be essential. Similarly, the consideration of different thermal properties for each layer was not required although several studies show that heat conduction is significantly lower in the epidermis than in the dermis for instance (see data collection in [26]).

The modeling of thresholds for nominal spot diameters smaller than 1 mm requires the assumption of a heat source of about 1 mm; this could be seen as minimum effective spot size similar to α_{min} for the retina. ED_{50} prediction was by far too low without this assumption. It is worthy to mention that 7 of the 8 concerned ED_{50}s were obtained in melanated in-vivo models (Yucatan pigs). This might be explained by scattering in the epidermis since the size of the heat source is of greater importance as the spot size diminishes. Another possible explanation pertains to the ability to detect very small superficial redness on a dark skin due to the lack of contrast.

Also we would like to note that the best fit of the experimental data was achieved by setting the parameters that would model blood flow to zero. Apparently, in other studies where blood flow was modeled, the blood flow parameter was set to very small values, so that it was not different from zero (e.g. [4]).

Comparison with MPEs

In the bio-effects and laser safety community, there is often a general notion and assumption that the reduction factor between the injury threshold and the exposure limit (MPE) is generally very large. However, before our study, no comprehensive data collection was available for a wide range of wavelengths and pulse durations (a two dimensional data base) as the basis for characterizing the "safety factor" or reduction factor. The data shown in Fig. 4 and Fig. 5 show that the MPE trend in terms of wavelength follows the trends of the thresholds in an approximate way, as was also known from modeling work of the cornea [27]. It is noted that the reduction factor in terms of wavelength is smallest for the wavelength range with high water absorption (3 µm, 10.6 µm) but we also find low thresholds in the blue wavelength range that can be expected to further decrease in the UV wavelength range, where for high peak powers and short pulses, the injury threshold for thermally induced injury can be expected to be lower than the photochemical injury threshold. The UV range was at this point in time not included in the validation range due to the lack of experimental data, however, following the validation for the available data, an extrapolation into the UV wavelength range should produce valid data and will be done in a follow-up study. Also we point out that our model in the green (and blue) wavelength range tends to predict thresholds that are lower, by a factor of about 1.5, as compared to the experimental data. Experimental data show that the CO_2 laser thresholds are a factor of about 2 lower than the thresholds for the green wavelength for a pulse duration of 1 s (lightly pigmented humans, see [9]).

In terms of dependence on pulse duration, for exposure to pulses, the range of about 100 ms produces the smallest reduction factors of about 3 for CO_2, Er:YAG lasers as well as blue-green wavelengths. Modeling work for retinal injury showed that there is little multiple pulse additivity in the large spot range. As for the retina in this regime (following the updated exposure limits), there is no pulse reduction factor needed for multiple pulse exposures.

For very long exposure durations, longer than 10 s, where the MPE remains a constant irradiance value, the reduction factor decreases because the injury threshold continues to decrease when presented as irradiance. However, when normal pain reaction is assumed and some minimal body movement, this should not be a practical issue, and at 100 s exposure duration, there is still a reduction factor of about at least 2-3 depending on wavelength.

Conclusions

Thermally-induced minimal injury of the skin (erythema) can be predicted adequately by using the model described here. Against 93 experimental data, the largest overestimation of threshold level in terms of energy was 84% and the lowest underestimation was -48%. This model can be used to study wavelength, pulse duration and spot size trends for comparison with MPE values or direct product safety analysis in the following range of exposures: wavelength (500 nm to 10.6 µm), spot size (240 µm to 20 mm) and exposure duration (350 µs to 70 s).

A comparison with the MPE values shows that, while the reduction factor is certainly sufficient to preclude thermal injury at levels below the MPE even for highly pigmented skin, it is - for some wavelengths and pulse

durations - not as large as it is sometimes portrayed, and can be as low as about 3.

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