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Prediction of temperature and damage in an irradiated human eye during retinal photocoagulation

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ABSTRACT

The goal of the study is improving the process of titrating laser power to the level of a "mild" coagulation when the damage to the retinal pigmented epithelium (RPE) sells is only performed, but coagulation of photoreceptors is avoided. An analytical thermal model of the irradiated eye tissue is proposed based on the solution of the heat equation for the laminar media having discrete optical properties. Both single-pulse and multi-pulse laser modes are under consideration. The model is applied for predicting the over-threshold heating within the lesion depending on its diameter. It is found that the size of the lesion detected after trial irradiation is a key factor that can be used for correcting the trial power to the level of mild coagulation. The corresponding correction function is introduced that is independent on eye media transmittance. Consequently, the proposed semi-empirical approach to the threshold prediction completely excludes the problem of unknown intraocular transparency. The transmittance-independent criterion of a critical lesion size is introduced, at which the axial superheat does not exceed a predetermined safety level regardless of pulse duration. The critical lesion dimensions are calculated for different diameters of irradiated spot at the retina. The analytical model is validated against experimental data available in literature.

1. Introduction

Retinal laser therapy is based on the selective photo-thermal effect of laser irradiation causing a predominant heating within the retinal pigmented epithelium (RPE) that is the main light absorbing layer in the eye tissue. During retinal photo-thermal treatment, the laser beam locally heats the irradiated spot. This may give a cure but it can also cause a problem [1]. Heating to the temperatures higher than that required to treat the diseased tissue can result in inadmissible damage to the adjoining healthy regions such as neural retina, photoreceptors and choroid, and vice versa, insufficient heating can lead to under-treatment. Hence, to make the treatment safe and effective, the light dose must be strictly monitored.

Recent advances in laser technology are associated with reduction of treatment intensity aimed to minimize or completely exclude adverse post-treating complications while maximizing the therapeutic effect [2]. Several alternative approaches have been investigated in this regard, including the concept of subthreshold diode micropulse (SDM) laser, whose intensity is minimized to levels that initiate the RPE photo-thermal stimulation, but do not cause permanent or visible damage to retina. One of the SDM modalities aimed to provide "mild" coagulation (i.e. coagulation of the RPE cells only and avoiding damage of the photoreceptors) is proposed in [3,4]. The concept involves delivery of a "train" of laser micro-pulses, each pulse separated by sufficient time to allow heat dissipate from the heated spot. The procedure includes two steps: firstly, the threshold is determined for individual patient by supplying several pulse trains with gradual increase in power until reaching barely visible burn at retina. Once the threshold is determined, the multi-pulse treatment to be performed with power reduced to 30–50% of the threshold.

Recently, a new clinical approach to the use of SDM technique was reported [5,6] that is defined as low-intensity subvisible diode micropulse treatment. According to this technique the laser doses are used that are significantly below the coagulation threshold which completely exclude RPE or retinal damage detectable by any means at the time of treatment or anytime thereafter.

Regardless of the sub-threshold technique used, the knowledge of the threshold itself is the most important condition for the safe laser application. This dose may be determined by individual titration of the laser power with gradual approach to the visible lesion endpoint. In this connection, an important question should be clarified: at what point of time the lesion is ophthalmoscopically determined? Often in clinical practice, what is referred to as a

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Nomenclature

κ	thermal conductivity
C_p	thermal capacity
γ	density
a^2	$=\kappa/(\gamma\ C_p)$ thermal diffusivity
α	absorption coefficient
h	layer thickness
n	number of layers
P	light power at RPE level
N	total number of laser pulses
R_b, D_b	beam radius and diameter (for Gaussian beam: at e^{-2} of the maximum intense)
F	$=\pi R_b^2$ area of the irradiated spot at the retina
R_v, D_v	radius and diameter of the lesion at the retina
z	coordinate along beam axis (counted from the front of the first absorbing layer)
r	radius
t	time
t_1	pulse duration
t_2	pulse period
τ	total time of exposure at elevated temperature
ρ, ϑ, ζ	cylindrical coordinates
R	$=\sqrt{r^2+\rho^2-2r\rho\cos\vartheta+(z-\zeta)^2}$
T	temperature
θ	temperature rise (heating) over the initial temperature
θ_p	temperature rise per 1 W of incident beam power
$H(u)=\begin{cases}0, & u<0\\ 1, & u\geqslant 0\end{cases}$	Heaviside unit step function
erfc(x)	complementary error function

"barely visible burn" is an immediately visible lesion endpoint. It should be noted that this threshold causes damage not only to RPE sells, but also to photoreceptors (and possibly to inner retina and choroid [7]), while lesions related to the minimal threshold doze (required for RPE coagulation only) may be not even seen 1 h after exposure and may become visible in 24 h [8]. It is clear that such a long titration protocol is incompatible with clinical practice, and this is the reason why for the milder treatment the laser dose is then reduced compared to the immediately visible lesion threshold.

Possible way to avoid the titration phase or at least to minimize the number of test pulses would be developing the reliable theoretical method for threshold predicting. Two physical models should be involved for this purpose: the thermal model of irradiated eye tissue based on solution of heat equation and the model of thermal damage based on Arrhenius integral [9]. Many studies are devoted to the development of this concept [10–17]. Birngruber et al. [10] were the first to offer an analytical thermal model of the irradiated eye tissue and used this approach for description of retinal photocoagulation. The single pulse model with two heat absorbing layers was under consideration. Majority of farther related researches are based on numerical finite-volume algorithms.

Although the theoretical approach gives an advantage of understanding the laser induced thermal processes, the accuracy of temperature and damage calculations is limited due to the uncertainty in the eye tissue physical properties, such as pigmentation intensity, ocular transmittance and damage model parameters (the RPE pigmentation can vary in humans by factor of two [18] and also a strong age-related variation of the ocular transmittance is a factor of strong uncertainty [19]). Since these parameters are the necessary inputs, the thermal models become incomplete and hence the accurate prediction of temperature courses and thermal thresholds is not possible. In such conditions, the only available scenario, which is widely used in practice, is a validation of the thermal model by comparing calculated and experimental results. The unknown inputs, mostly intraocular transmittance or absorbance, are used as free parameters to fit calculations to experimental results [17,20,21]. In fact, this approach is an indirect identification of the unknown input data, it can not be qualified as a threshold prediction, and therefore the need for individual titration retains.

In this paper, a theoretical analysis of the processes in the eye tissue exposed to multi-pulse laser irradiation is given and the method is proposed for predicting the necessary correction of the trial pulse power to obtain a "mild threshold". To avoid misinterpretation, we will refer to as a "mild" (or minimal) threshold the doze that is necessary to produce damage to the RPE sells only with sparing the photoreceptors. The lesions associated with these thresholds will be considered as detected during the post-exposure time that is necessary to ensure their full development. An analytical multi-layer multi-pulse thermal model used in this study is related to the authors' earlier publication [22] so we give here the final solution without details of its derivation. An important peculiarity of this study is representing the solution in the form of a specific increase in temperature per 1 W of the irradiance power incident on the retina. This allows considering the Arrhenius damage integral as one-variable function of power, what greatly simplifies its estimation. The wide spectrum of calculations was undertaken using this approach with detailed description of the spatial and temporal thermal profiles in the irradiated eye tissue. The temperature distribution inside the lesion, which corresponds to the threshold heating at its periphery, is considered in details for both Gaussian and top-hat beam profiles. It is found that the size of the lesion detected after trial laser irradiation is a key factor that can be used for correction of the laser power to the mild threshold that is necessary to coagulate the RPE sells with sparing retina. The advantage of this semi-empirical approach is in the fact that no knowledge of the intraocular transmittance is necessary for its application. Consequently, the problem of unknown intraocular transparency is completely eliminated. Basing on this analysis, the concept of the critical lesion size is introduced, at which the risk of unacceptably high on-axis heating is excluded at any pulse duration. The range of exposures from 0.05 ms to 1 s is considered in which the thermal denaturation is a prevailing damage mechanism, with emphasis on the pulse durations from 0.1 to 1 ms, the time when heating is confined to RPE boundaries to the benefit of its selective coagulation. The analytical model is validated against experimental data available in literature.

2. Thermal model

We consider the following thermal problem. Given is a layered structure having discrete optical properties of individual layers. Initial temperature of the structure T_0 is uniform. At time point $t = 0$, the structure is subjected to laser irradiation. Accordingly, an axially symmetric heat source arises within the structure due to absorption of light energy. Heating continues until the time point t_1, then the laser is turned off and cooling takes place until the point $t_2 > t_1$ due to heat conduction from the heated area into surrounding tissue. Then this cycle is repeated multiple times. It is