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Thermal interaction of multi-pulse laser beam with eye tissue during retinal photocoagulation: Analytical approach

Vladimir Semenyuk

Thermion Company, 9/11 Tenistaya st., Odessa 65009, Ukraine

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ABSTRACT

The laser-induced temperature disturbance within retinal pigmented epithelium (RPE) and in the adjacent layers of a human eye is studied with the aim to specify laser optimal parameters providing safe treating. Proposed is a generalized model of a laser irradiated multi-layered media with arbitrary number of layers having uniform thermal and discrete optical properties. An analytical approach is used that allowed obtaining description of the spatial and temporal evolution of the temperature in the irradiated media. The required maximum temperature is kept as a preassigned value, and the search for necessary laser parameters is subjected to this condition. Calculations are made for Gaussian and uniform (top hat) lasers with wavelengths 514, 532 and 577 nm. Necessary combinations of pulse power and its duration that provide predetermined peak temperature within RPE are identified. The possible inter-individual deviations of eye physical properties are reviewed and probable risks of RPE overheating arising from these uncertainties are evaluated for the first time. The advanced concept of sub-threshold multi-pulse laser treatment is analyzed. The method for definition of necessary pulse train parameters for maintaining the target RPE temperature at the end of the pulse train is proposed. Analytical model is validated in a wide range of laser parameters against state-of-the-art theoretical and experimental data available in the literature.

1. Introduction

Over the past decades, lasers found wide application in ophthalmology for treating a variety of functional and age-related retinal pathologies [1–4]. The therapy is based on the selective photothermal effect of laser irradiation causing a predominant heating within the retinal pigmented epithelium (RPE) that is the main light absorbing tissue in the eye [5]. During laser surgery, the laser beam locally heats the irradiated spot. This may give a cure but it can also turn to be a problem [4]. Heating to the temperatures higher than that required to coagulate 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 eliminate possible hazards and make the treatment effective, the light dose must be strictly monitored.

Possible way to get treatment controlled is to elaborate a reliable physical model of the intra-ocular temperature evolution for predicting necessary laser parameters. Many studies are devoted to the solution of this problem [6–13]. Birngruber et al. [6] were the first to offer an analytical approach to describing the temporal and spatial evolution of the temperature in the irradiated eye tissue. The single pulse model with two heat absorbing layers was under consideration. Majority of farther researches are based on numerical evaluation of transient temperature disturbance in the eye, induced by laser irradiation. The following question is typically discussed: what would be temperature elevation for given pulse power, its duration and duty cycle? Sometimes, such approach leads to demonstrating unacceptably high heating as a response on randomly chosen laser parameters [7]. Meanwhile, just the needed temperature rise has to be considered as a primary factor that must be strictly held. Hence, the selection of the laser parameters (wavelength, pulse power, its exposure time and frequency, beam diameter and required number of pulses) that would provide recommended heating in the necessary point of the eye tissue seems to be the most reasonable approach aimed to safe laser application.

In this study, the required maximum temperature is considered as a preassigned value and the search for necessary laser parameters is subjected to this condition. Proposed is a generalized model of laser irradiated multi-layered structure with arbitrary number of layers having individual light absorption properties. Generally, this model is applicable in various fields of laser medicine for

E-mail address: semeniouk@thermion.tenet.odessa.ua

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analysis of thermal interaction between laser beam and human tissue having complex structure with individual optical properties of the component layers. In this paper, the proposed theoretical approach is used for description of the temperature evolution in the ocular media exposed to laser irradiation during selective retinal photocoagulation. In contrast to the majority of other studies, where numerical finite-element method is applied, an analytical approach is used, which in combination with effective computational algorithms provides quick and accurate calculation of the peak temperature and its location in the eye tissue. This allowed undertaking the wide spectrum of calculations with detailed description of the spatial and temporal thermal profiles in the irradiated eye fundus. Lasers with wavelengths 514, 532 and 577 nm including both Gaussian and uniform (top hat) profiles are considered in single pulse and multi-pulse modes of operation. Recommendations are obtained concerning the required combination of pulse power and its duration for maintaining the predetermined peak temperature within RPE. Calculations are based on the typical values of human eye physical parameters. The possible inter-individual deviations of these parameters from those accepted in calculations are reviewed and an impact of this uncertainty on temperature profile is firstly estimated. The advanced concept of sub-threshold multi-pulse treatment is under consideration. The method for definition of the necessary pulse power, their number and frequency required to maintain given RPE temperature at the end of the pulse train is developed. Proposed analytical model is validated against theoretical and experimental data available in the literature.

2. Theoretical approach

2.1. Formulation of the thermal problem

We assume the human eye as a thermally uniform and optically discrete body. As the laser affected zone is negligibly small comparing to the eye overall dimensions, it is modeled as an infinite media whose initial temperature T_0 is accepted to be uniform. At the time $t = 0$, the axially symmetric heat source $q(r,z)$ is activated within this body. Heating continues until the moment t_1, then the power is turned off and cooling takes place until the moment $t_2 > t_1$ due to heat conduction from the heated area. Then this cycle is repeated multiply. It is necessary to find the distribution of the excess temperature $\theta(r,z,t) = T(r,z,t) - T_0$ as a function of position and time.

2.2. General solution

In our model considered are pulse durations between 10 μs and 1 s, the range in which individual heating of separate melanin granules within RPE can be ignored and also effect of heat convection due to blood flow may be neglected [6]. Hence, the heat conduction equation for an infinite solid is applicable for description of heat transport in the eye. Solution of this thermal problem is obtained by means of a source function in the following form [14]:

$$\theta(r,z,t) = \frac{1}{4\pi\kappa}\int_{-\infty}^{\infty} d\varsigma \int_0^{R_b} q(\rho,\varsigma)\int_0^{2\pi}\frac{1}{R}erfc\left(\frac{R}{\sqrt{4a^2t}}\right)\rho d\rho d\vartheta \quad (1)$$

where

$$R^2 = r^2 + \rho^2 - 2r\rho\cos\vartheta + (z-\varsigma)^2 \quad (2)$$

κ and $a^2 = \kappa/(\gamma c_p)$ – are eye tissue thermal conductivity and thermal diffusivity respectively, γ – is density, c_p – is thermal capacity, R_b – is the beam radius, erfc(x) – is the complementary error function, ϑ – is an angle; beam axis coincides with z-axis.

Here in Eq. (1) the heat source volume density $q(r,z)$ is an arbitrary function of coordinates. To get the concrete solution for the case under consideration, it is necessary to specify the source function $q(r,z)$.

2.3. Laser as a heat source

Considered is the axis-symmetric monochromatic laser beam with Gaussian profile. In that case, the coordinate dependence of the beam power density (intensity) can be expressed as

$$I(r,z) = I(0,z)\exp\left(-2r^2/R_b^2\right) \quad (3)$$

Here the function $I(0,z)$ represents on-axis intensity, while the exponential term determines its transverse distribution. The Gaussian beam radius R_b is defined as that at which intensity gets decreased to $1/e^2$ of its axial value.

For monochromatic beam, its intensity obeys the Lambert-Beer's law that sets an exponential decrease in the beam power with the depth in the irradiated material due to light absorption

$$I(0,z) = I_0\exp(-\alpha z) \quad (4)$$

where I_0 – is the incident beam on-axis intensity, α – is the wavelength dependent absorption coefficient of the irradiated media.

The local density of heat dissipation within the irradiated tissue $q(r,z)$ is defined as a derivative $-\partial I(r,z)/\partial z$ what gives in view of Eqs. (3) and (4):

$$q(r,z) = I_0\alpha\exp(-\alpha z)\exp\left(-2r^2/R_b^2\right) \quad (5)$$

2.4. Modeling of multilayer tissue

We consider the eye tissue as a multi-layered media with uniform thermal and discrete optical properties. Given are layer thicknesses h_i and their absorption coefficients α_i, $i = 1,\ldots,n$. Laser beam enters into the layer normal to its surface. The z-axis origin coincides with the frontal surface of the first layer. Let I_{0k} is the incident on-axis intensity for k-th layer. Then, in accordance with the Lambert-Beer's law, the outlet beam intensity for this layer decreases down to $I_{0k}\exp(-\alpha_k h_k)$. With scattering and reflectance in the absorbing tissues neglected [5,10], the axial beam intensity at layer interfaces must obey the continuity conditions given by the recurrent formula: $I_{01} = I_0$; $I_{0k+1} = I_{0k}\exp(-\alpha_k h_k)$, $k = 1,\ldots,n-1$, that reduces to the following relations:

$$I_{0k} = I_0 A_k, \quad k = 1,\ldots,n \quad (6)$$

where

$$A_1 = 1, \quad A_{k+1} = \exp\left(-\sum_{i=1}^{k}\alpha_i h_i\right), \quad k = 1,\ldots,n-1 \quad (7)$$

We suppose that the incident beam axial intensity at the first (anterior) layer I_0 is a specified quantity. So Eqs. (6) and (7) allow calculating the incident intensities for all subsequent layers. Within each layer the intensity varies exponentially according to Eq. (4). Applying Eqs. (5)(7) to each layer and assuming that heat absorption outside the range $(0, z_n)$ is negligibly small, one obtains the local heat release $q(r,z)$ in the form:

$$q(r,z) = I_0\exp\left(-\frac{2r^2}{R_b^2}\right)\cdot\begin{cases}0, & z < 0\\ \alpha_k A_k\exp(-\alpha_k(z - z_{k-1})), & z_{k-1} \leqslant z < z_k,\ k = 1,\ldots,n\\ 0, & z > z_n\end{cases} \quad (8)$$

where $z_0 = 0$, $z_k = \sum_{i=1}^{k} h_i$.