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Transient simulations of heat transfer in human eye undergoing laser surgery

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ABSTRACT

A validated two-dimensional computational model of the human eye solving the discretized form of the bio-heat transfer equation using finite volume formulation has been developed. Using the model, the transient temperature evolution and associated thermal effects in various regions of the human eye subjected to laser radiation during retinopathy are investigated. It is shown that the transient evolution of the retinal temperature during laser heating could reach values higher than that required for irreversible cell damage. This is because the time scale for spatial diffusion of heat towards the choroid, containing blood vessels for cooling, is much larger than that of the actual laser surgical process (100 ms). This excess temperature could cause cell damage to the adjoining retinal region due to heat diffusion. Based on the simulation results, a method is proposed to maintain the retinal pigmented epithelium (RPE) temperature close to the required 60 °C by pulsating the laser source between suitable maximum and minimum heat flux values.

1. Introduction

Temperature induced biological effects can be pronounced in the eye due to insufficient cooling by blood flow, the predominant thermal management mechanism of the human body. During laser treatment of the retina, the human eye has to physiologically cope with temperatures higher than 60 °C. Ophthalmologic laser applications include use of laser irradiation to create localized controlled thermal burns or coagulation within the eye and the use of laser-induced photodegradation of diseased tissue. Since the photocoagulation temperature is around 60 °C, overheating could disrupt cellular mechanism in regions adjoining the target zone, resulting in malfunction or damage to the eye [1–3]. Direct *in vivo* temperature monitoring in the interior of a live human eye is not yet completely possible. Numerical simulations using the computers can help optimize conditions, setting parameters for safe laser based treatments.

For simulating and optimizing laser therapy or surgery in ophthalmology, it is essential to compute the heat transfer and the resulting temperature variation within the eye during laser irradiation. Numerical models of heat transport in the eye have been studied in the past as quantitative approximations of the complex physiological system. An early model of the eye was developed by Al-Badwaihy and Youssef [4] for examining the thermal effects of microwave radiation. They developed an analytical method of solution for the steady state temperature distribution, with an assumed combined (convection and radiation) heat transfer coefficient as that of the rabbit eye. Considering eye as a homogeneous tissue, Taflove and Brodwin [5] reported a model using a finite difference method of solution, assuming a constant convection heat transfer coefficient over the entire surface of the eyeball. This resulted in the frontal sections of the eye i.e. cornea (see Fig. 1) being practically indistinguishable from the posterior sections such as sclera and the body core. Owing to the assumption of homogeneity, the effect of lens as a thermal barrier is lost. Further, the assumed initial ($t = 0$ s) temperature of the entire eye to be at a uniform temperature of 37 °C is also unsuitable since the transient solution is dependent on the initial temperature distribution of the eye that varies between the temperatures of the sclera and cornea.

Emery et al. [6] presented a finite element heat transport model for the rabbit eye. This model was used for calculating the initial temperature distribution of normal rabbit eye and eye exposed to microwave radiation. Using a computational grid that approximated the shape of the lens and other structures, models of the human and rabbit eyes were presented by Lagendijk [7]. Employing an explicit forward difference scheme, both transient and steady state calculations were performed. A two-dimensional finite element model of heat transport in the human eye was reported by Scott [8], using the bio-heat transfer equation. Steady-state temperature variation was considered in the human eye when exposed to infrared radiation. Another two-dimensional finite element model by Scott [9] calculated temperature change in the intra-ocular media in the human eye when it is exposed to infrared

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Nomenclature

c	specific heat (J kg^{-1} K^{-1})
D	distance from cornea (mm)
E	evaporation rate of tear (W m^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
$\dot{m}$	mass flow rate (kgs^{-1})
Q	heat power (W)
q''	heat flux (W m^{-2})
Q'''	heat generation rate (W m^{-3})
RPE	retinal pigmented epithelium
T	temperature (°C)
t	time (ms)

Greek symbols

α	thermal diffusivity (m^2/s)
ε	emissivity
η	unit outward normal (m)
γ	absorptivity (%)
λ	thermal conductivity (W m^{-1} K^{-1})
ω	perfusion rate (kg m^{-3} s^{-1})
ρ	density (kg m^{-3})
σ	Stefan–Boltzmann constant (W m^{-2} K^4)

Subscripts

a	ambient
avg	average
b	body
bl	blood
c	cornea
lp	laser path
r	center of RPE
ravg	volume averaged RPE
s	sclera
t	tissue

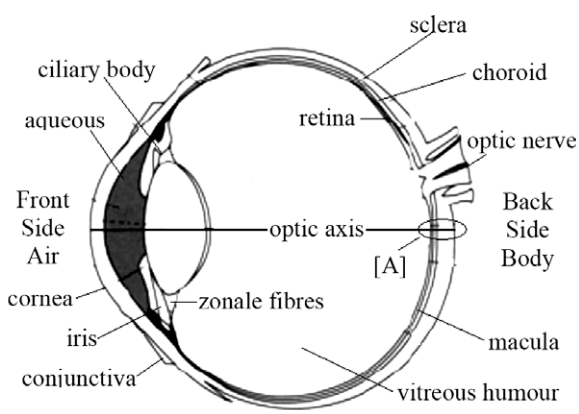

Fig. 1. Schematic of the physiology of the human eye.

radiation. This model considered both transient and steady state solutions, showing that the temperature variation in the anterior segment of the eye can occur if an increase in evaporation from the anterior corneal surface and rapid blink factors are present simultaneously.

Amara [10] presented a numerical thermal model of laser–ocular media interaction. A similar model was presented recently by Cvetkovic et al. [11]. Their models describe the effect of laser radiation on eye but does not aim to relate clinical applications such as laser surgery of eye. Thompson et al. [12] presented a numerical granule model of laser absorbance in RPE considering spherical shape of cone and receptors present, which deviates from the conical shape of cone and receptors. Additionally, it does not consider the bulk volume affected during laser surgery. Recently, Chua et al. [13] presented a numerical model to predict the temperature distribution within the human eye when subjected to laser source using only four ocular tissues along the central pupillary axis (see Fig. 1). The initial temperature of the eye was assumed to be constant throughout the eye. A complete geometry of the eye was also not considered. In an excellent study, Flyckt et al. [14] studied the impact of several values for the choroidal convection heat transfer coefficient, the essential cooling effect due to the blood flow in the choroid. Using numerical simulation of heat transport along a simple three-dimensional geometry of the eye, they explored much higher values for the choroidal heat transfer coefficient from that of an earlier study [7] involving one of the authors. Similar simple three-dimensional model was presented by Ng and Ooi [15] and Ng et al. [16], extending from their two-dimensional model [17,18]. These were restricted to steady state results. A transient model for corneal laser surgery (thermokeratoplasty) using boundary element method was recently presented by Ooi et al. [19].

In this study, a geometrically identical, full scale two-dimensional finite volume numerical model of the human eye is developed to investigate the transient temperature evolution and its effects inside the human eye subjected to laser irradiation. The present model incorporates the bio-heat transfer equation. Using this model, the influence of material properties, external thermal conditions and the effect of choroidal blood convection cooling on the transient laser heating and subsequent cooling of the retina are investigated in detail.

2. Mathematical formulation and boundary conditions

In order to find the temperature distribution during laser surgery, it is essential to solve the energy equation within the eye domain with necessary boundary conditions. The Pennes bio-heat transfer equation [20] can be written as

$$\rho c_t \frac{\partial T_t}{\partial t} = \nabla(\lambda \nabla T_t) + Q''' + \dot{m}_{bl} c_{bl}(T_{bl} - T_t) \quad (1)$$

where Q''' is the heat source or generation/absorption in each region of the eye due to external laser irradiation. Table 1 explains how Q''' values are arrive at. The percentage of absorbtion of laser in a particular tissue is obtained from experimental results published by Boettner and Wolter [21] and Chew et al. [22]. By using this method, the required radiation flux modeling of the laser is circumvented for simplicity. Even though the duration of the process is short, the possible effect of a non-Fourier type conduction in the RPE is also not considered. However, the model does not lack any generality and predicts the upperbound RPE thermal characteristics, as the laser power input remains fixed in the transient process. The last term in Eq. (1) is the blood perfusion arising due to blood flow through the tissue. Since this term models blood flow, it contributes predominantly in modeling the choroidal blood flow at the rear of the eye as a cooling mechanism during laser irradiation. The choroidal blood mass flow rate can be calculated as

$$\dot{m}_{bl} = \omega \times V_c \quad (2)$$

where ω is the blood perfusion rate and V_c is the volume of the choroid in the interior of eyeball. Suitable values for ω are taken from Flyckt et al. [14] and the other literature.