International Journal of Thermal Sciences 50 (2011) 1191–1198

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Three-dimensional bio-heat transfer simulation of sequential and simultaneous retinal laser irradiation

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ARTICLE INFO

Article history:
Received 2 August 2010
Received in revised form
8 December 2010
Accepted 8 February 2011
Available online 21 March 2011

Keywords:
Three-dimensional model
Bio-heat transfer
Laser surgery
Eye
Transient simulations
Retina
Multi spot
Square array

ABSTRACT

Transient simulation of retinal laser irradiation is performed for a square array comprising 3 × 3 uniformly distributed spots under sequential and simultaneous mode. A finite volume formulation of the Pennes bio-heat transfer model is employed as the governing equation to generate the temperature distribution within the eye domain. Temperature distribution developed due to laser power of 0.2 W/spot and time duration of 100 ms/spot is used to compare the merits of sequential and simultaneous irradiation of spots. Simultaneous mode is preferred when the time of surgery is limited, with possible excess heating in the inter-spot retinal regions. The inter-spot spacing D is also varied between one diameter and one and half diameter of the spot size (diameter) to evaluate the safe placement of consecutive spots. $D \geq 0.75$ mm can be considered as the optimum spot distance for non-interference due to excess heating. Effect of pulsation of incident laser power is observed to favorably reduce the average temperature of the irradiated regions of the retina toward photocoagulation temperature.

1. Introduction

Laser finds frequent application in a process called Pan-Retinal Photocoagulation (PRP), a surgical treatment for diabetic retinopathy and macular degeneration of the human eye. PRP treatment for retinal ailment selectively coagulates retinal regions (Retinal Pigmented Epithelium – RPE) through laser irradiation. The success of such laser surgical process depends on the prediction and control of temperature in the irradiated tissue, in order to selectively destroy the target regions without affecting surrounding regions. Overheating could disrupt cellular mechanism in regions adjoining the target tissue, resulting in malfunction or damage to the eye [1–3]. Thus prior knowledge of temperature distribution in the entire region of treatment is essential to control the temperature and prevent damage to healthy tissue.

Accurate experimental determination of temperature field during such live surgical process is not yet possible due to limitations in non-invasive measurement of temperature and also ethical constraints and pain tolerance of patient with invasive processes [4]. Hence analysis and computer modeling of such bio-heat transfer process can assist ophthalmologists in prescribing safe and efficient procedures.

The Pennes bio-heat model [5] is often preferred for its simplicity, validity and its wide-spread applicability in less vascularized tissues. Considering eye as a homogeneous tissue, Taflove and Brodwin [6] reported a model using a finite difference method of solution, assuming a constant convection heat transfer coefficient over the entire surface of the eyeball.

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 exposed to infrared radiation. This model considered both transient and steady-state solutions.

A numerical heat transport mode of human eye considering laser-ocular media interaction was presented by Amara [10]. A similar model was presented recently by Cvetkovic et al. [11]. Their models

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1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2011.02.005

Nomenclature

c	specific heat, J kg^{-1} K^{-1}
D	center-to-center distance between two consecutive spot, mm
h	heat transfer coefficient, W m^{-2} K^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
PRP	pan-retinal photocoagulation
Q	heat power, W
Q'''	volumetric heat generation rate, W m^{-3}
RPE	retinal pigmented epithelium
T	temperature, °C
t	time, ms

Greek symbols

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}

Subscripts

b	body
bl	blood
c	choroid
r	center of RPE
s	sclera
t	tissue

describe the effect of laser radiation on eye to enhance laser safety regulations, but do not aim to relate clinical applications such as laser surgery. Recently, Chua et al. [12] 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 complete geometry of the eye was not considered. Kandulla et al. [13] presented a method to monitor the online temperature during the laser surgery of long duration of the human eye, but observation was not extended to short duration laser surgery. The study was further extended by Sandeau et al. [14].

Flyckt et al. [15] 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 in a simple three-dimensional geometry of the eye, they studied effects of stronger choroidal convection than an earlier study [7] involving one of the authors. A simple three-dimensional model was presented by Ng and Ooi [16] and Ng et al. [17], extending their two-dimensional model from Ng et al. [18] and Ooi et al. [19]. These were restricted to steady-state results. A transient numerical model of human eye for corneal laser surgery (thermokeratoplasty) using boundary element method was presented by Ooi et al. [20]. A similar model for eye tumor was also presented by Ooi et al. [21] in continuation of their earlier models [22].

The present study involves three-dimensional transient simulations of multi-spot retinal laser surgery considering the sequential and simultaneous irradiation of spots of a square array. Finite volume formulation of Pennes bio-heat transfer is employed as the governing equation to simulate the transient temperature distribution in human eye. Based on the outcome of such temperature distribution, merits of sequential and simultaneous irradiation of spots and associated thermal damages due to excess heating and possible solutions are discussed in detail.

2. Mathematical formulation and boundary conditions

In order to find the resulting temperature distribution due to laser surgical process with the eye domain, one must solve the energy equation with necessary boundary condition. The Pennes bio-heat transfer equation can be written as

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

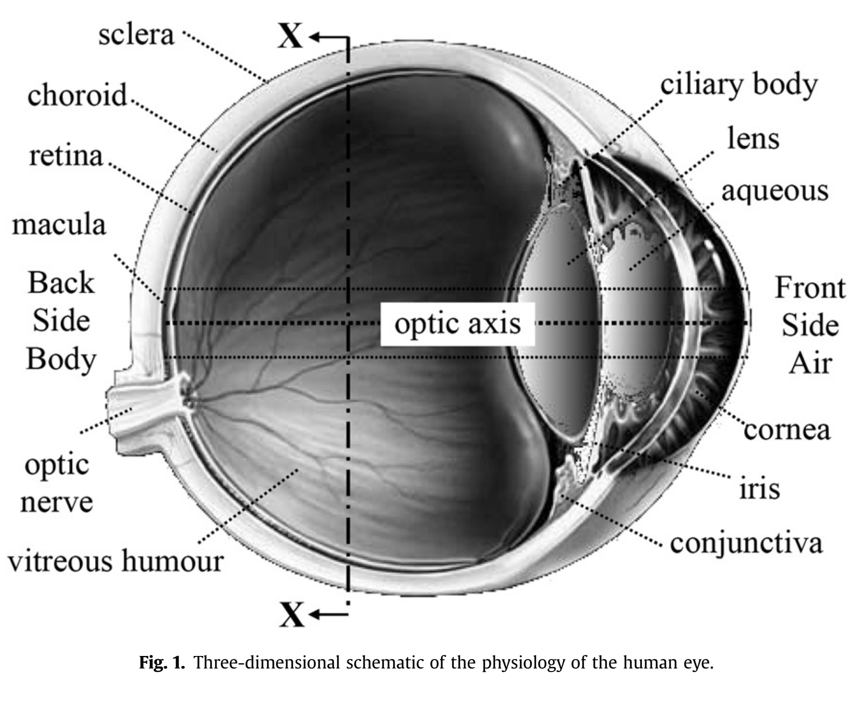

Fig. 1. Three-dimensional schematic of the physiology of the human eye.