Journal of Thermal Biology 49-50 (2015) 74–81

Contents lists available at ScienceDirect

Journal of Thermal Biology

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

A comparative study of thermal effects of 3 types of laser in eye: 3D simulation with bioheat equation

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ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form
10 February 2015
Accepted 10 February 2015
Available online 13 February 2015

Keywords:
Pennes bioheat equation
Blood perfusion
Nd:Yag laser
Nd:Yap laser
Argon laser

ABSTRACT

The application of laser in ophthalmology and eye surgery is so widespread that hardly can anyone deny its importance. On the other hand, since the human eye is an organ susceptible to external factors such as heat waves, laser radiation rapidly increases the temperature of the eye and therefore the study of temperature distribution inside the eye under laser irradiation is crucial; but the use of experimental and invasive methods for measuring the temperature inside the eye is typically high-risk and hazardous. In this paper, using the three-dimensional finite element method, the distribution of heat transfer inside the eye under transient condition was studied through three different lasers named Nd:Yag, Nd:Yap and ArF. Considering the metabolic heat and blood perfusion rate in various regions of the eye, numerical solution of space–time dependant Pennes bioheat transfer equation has been applied in this study. Lambert–Beer's law has been used to model the absorption of laser energy inside the eye tissues. It should also be mentioned that the effect of the ambient temperature, tear evaporation rate, laser power and the pupil diameter on the temperature distribution have been studied. Also, temperature distribution inside the eye after applying each laser and temperature variations of six optional regions as functions of time have been investigated. The results show that these radiations cause temperature rise in various regions, which will in turn causes serious damages to the eye tissues. Investigating the temperature distribution inside the eye under the laser irradiation can be a useful tool to study and predict the thermal effects of laser radiation on the human eye and evaluate the risk involved in performing laser surgery.

1. Introduction

Since the invention of the first laser by Maiman in 1960, researchers have studied the miscellaneous applications of lasers in various fields. Laser surgery is definitely one the most important of these applications which is regarded as one of the most significant developments in the medicine of the present century. In fact, it can be claimed that different types of lasers have been proposed as unrivalled tools in modern medicine.

Laser systems have been divided into two categories: continuous wave lasers and pulsed lasers. Most gas lasers and some solid-state lasers belong to the first group, whereas pulsed lasers family mainly include dye lasers.

Medical lasers have important parameters. The time duration of laser radiation is a serious parameter for the interaction of laser with biological tissue. The second important parameter is the wavelength of the laser which defines the penetration depth of the laser into the tissue. The third parameter, which is the density of laser energy, is also significant. The fourth parameter that should be taken into account is the intensity of radiation, which by definition is the ratio of energy density to the pulse width.

Today, a variety of lasers are used to treat and diagnose diseases in ophthalmology. Since the use of laser in treatment of retinal detachment disease, this type of surgery is known as a common approach. Other applications of laser in this field include glaucoma and cataracts treatment (Niemz, 2007).

Numerical simulation of laser irradiation is a fast and easy assessment to predict the temperature distribution in the eye without the need for invasive tests. Taflove and Brodwin (1975) showed temperature distribution in the eye by a finite difference model. Using Pennes bioheat equation and invasive tests, Priebe et al. (1975) and Emery et al. (1975) proposed one of the first these computer models for temperature distribution inside rabbit eye. Lagendijk (1982) presented different mathematical eye models for

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http://dx.doi.org/10.1016/j.jtherbio.2015.02.004
0306-4565/

humans and rabbits in 1982 before Scott developed a FEM-model of the human eye in 1988. Based on these works, many different eye models have been developed until today. Ng and Ooi (2006) solved the temperature distribution inside the eye under steady state condition. In his model, three layers of retina, sclera and choroid were considered as a single layer. In previous works mentioned earlier, the effect of laser on the eye tissue was not investigated and the models only included the simplifying of the eye. On the other hand, numerical simulation of laser surgery has been performed by various scientists. Applying finite volume method, Narasimhan et al. (2010) numerically studied the two-dimensional transient heat transfer in laser surgery. Taking into account all the layers of the eye, the blood perfusion and metabolic heat in ciliary body and retina, Cvetković et al. (2008) analysed the effect of the Nd:Yag laser for the surgery of cornea. In his model, the effect of the blood perfusion and metabolic heat inside the choroid was not considered. Mirnezami et al. (2013) used his model to assess the irradiation of the whole eye, using only the scleral heat transfer and they did not consider all parts of eye in their model. Heussner et al. (2014) presented a three-dimensional thermo-dynamic model of the human eye for the prediction of temperatures and damage thresholds under irradiation and they consider blood flow in their simulation.

In this paper, the distribution of heat transfer inside the eye under transient condition was studied through three different lasers and the effect of the ambient temperature, tear evaporation rate, laser power and the pupil diameter on the temperature distribution have been studied. Finally, temperature distribution inside the eye after applying each laser and temperature variations of six optional regions as functions of time have been investigated.

2. Theoretical background

2.1. Anatomy

The eye is not shaped like a perfect sphere, rather it is a fused two-piece unit. The smaller frontal unit, more curved, called the cornea is linked to the larger unit called the sclera. Light enters the cornea from outside and after passing through the pupil reaches the lens. The lens focuses light precisely on the retina so that a clear image on the retina is created. Irradiation targets in laser treatment divide the eye into two anterior and posterior parts. The anterior part of the eye includes the cornea, iris and the ciliary body, while the posterior part of the eye is composed of lens, vitreous and retina. A schematic of the human eye can be seen in Fig. 1. (Niemz, 2007).

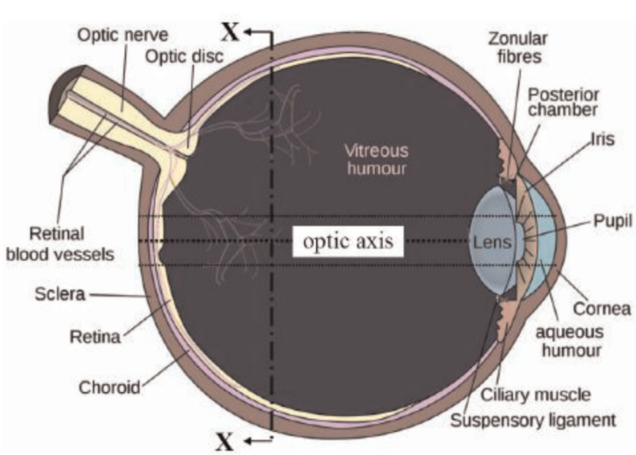

Fig. 1. A schematic of the human eye (Narasimhan et al., 2010).

2.2. Governing equations

2.2.1. Heat transfer equations

The governing equation in this simulation is the Pennes bioheat equation and its general form is as follows (Pennes, 1948).

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q + \rho_b C_b \omega_b (T_b - T) + Q_{met} \quad (1)$$

In this equation $\rho$is density, C_p is the specific heat, ω_b is the rate of blood perfusion, k is the thermal conductivity and Q_{met} is the metabolic flux. These values for each tissue can be seen in Table 1. Moreover, T_b is the blood temperature, C_b is the specific heat of blood and ρ_b is the density of blood which are equal to 37 °C, 3594 J/kg °C and 1060 kg/m^3, respectively.

Pennes bioheat equation is used due to the presence of blood perfusion and metabolic heat flux terms in this equation.

2.2.2. Laser equations

When modelling the laser source, one can use a simplifying fact that many laser beams are of a Gaussian profile. This consideration is valid when the beam divergence is very small as is the case for a laser. Thus, the solutions for the the intensity can be represented in the form of a Gaussian function. Beer–Lambert equation is used for applying the effect of laser. Energy density ($Q(r,z,t)$) absorbed by the tissues of the eye is defined using the following equation (Narasimhan and Jha, 2012).

$$Q(r, z, t) = \alpha I(r, z, t) \quad (2)$$

Where α is the laser wavelength, which depends on the absorption coefficient of the tissue. Absorption coefficients of each tissue are shown in Table 2 for all three lasers.

In Eq. (2), I is the intensity of the Laser which is defined as follows (Narasimhan and Jha, 2012).

$$I(r, z, t) = I_0 \exp\left(-\frac{2r^2}{w^2} - \alpha z \right) \exp\left(-\frac{8t^2}{\tau^2} \right) \quad (3)$$

In this equation, I_0 is the initial intensity of the laser, w is the diameter of the laser (0.5 mm) and τ is the pulse duration of the laser which are equal to 100 ns, 10 ms and 1 ms for Argon, Nd:Yag and Nd:Yap lasers, respectively. The most crucial characteristic of the eye tissues is the absorption coefficient resulting from its drastic dependence on the wavelength of the laser. Therefore, for different tissues of the eye, the absorption occurs at specific wavelengths.

3. Material and methods

In this paper, we used the three-dimensional finite element method, the distribution of heat transfer inside the eye under transient condition was studied through three different lasers named Neodymium-Doped Yttrium Aluminium Garnet (Nd:Yag), Neodymium-Doped Yttrium Aluminium Perovskite (Nd:Yap)and Argon Fluoride (ArF)with wavelengths of 1340, 1064 and 193 nm, respectively. Considering the metabolic heat and blood perfusion rate in various regions of the eye, numerical solution of space–time dependant Pennes bioheat transfer equation has been applied in this study. Lambert–Beer's law has been used to model the absorption of laser energy inside the eye tissues. It should also be mentioned that the effect of the ambient temperature, tear evaporation rate, laser power and the pupil diameter on the temperature distribution have been studied. Finally, temperature distribution inside the eye after applying each laser and temperature variations of six optional regions as functions of time have been investigated.