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Mathematical modeling of laser linear thermal effects on the anterior layer of the human eye

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ABSTRACT

In this paper, mathematical analysis of thermal effects of excimer lasers on the anterior side of the human eye is presented, where linear effect of absorption by the human eye is considered. To this end, Argon Fluoride (ArF) and Holmium:Yttrium-Aluminum-Garent (Ho:YAG) lasers are utilized in this investigation. A three-dimensional model of the human eye with actual dimensions is employed and finite element method (FEM) is utilized to numerically solve the governing (Penne) heat transfer equation. The simulation results suggest the corneal temperature of 263 °C and 83.4 °C for ArF and Ho:YAG laser radiations, respectively, and show less heat penetration depth in comparison to the previous reports. Moreover, the heat transfer equation is solved semi-analytically in one-dimension. It is shown that the exploited simulation results are also consistent with those derived from the semi-analytical solution of the Penne heat transfer equation for both types of laser radiations.

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1. Introduction

Lasers with different wavelengths have been used greatly in various medical fields such as dentistry, gynecology, neurosurgery, dermatology, orthopedics, gastroenterology, angioplasty, cardiology, and particularly in ophthalmology and eye surgeries [1]. These lasers are mainly short pulsed type and able to provide higher intensity which is desirable for medical applications. The main reasoning behind the use of this type of lasers is that they can provide more control on the amount of energy irradiated by the laser, amount of energy dissipation and also more precision on the zones of the eye that are heated by the laser. Also, in LASIK (Laser in Situ Keratomileusis) and PRK (Photorefractive Keractomy) surgeries dealing with vision correction, short pulsed lasers are well-absorbed by the corneal collagen of the eye in a more effective way and as a result the collagen is well-shrunk [2,3]. Absorption of laser light by different eye tissues leads to heat generation. However, due to the lack of blood circulation in most of the anterior part of the eye (especially cornea), the eye does not have the ability to reduce this temperature rise and hence damages to the tissues may occur. This issue should be taken seriously into account while employing laser in eye treatments. On the other hand, eye temperature measurement is not often possible by noninvasive methods; therefore, thermal analysis is required. This analysis should be accurate, reliable and repeatable.

The human eye consists of three main parts. Outer layer includes sclera and cornea; the middle part consists of the iris, aqueous humor, and choroid; and the retina and vitreous humor are considered the inner section of the human eye [4]. Fig. 1 shows a normal eye with actual dimensions. The cornea, which has ~0.5 mm thickness, plays the main role in refractive power of the eye [5]. The iris muscles by contraction help lens to change the focal distance which is known as eye's accommodation [6]. Then, the beam of light hits the retina; chemical changes occur and consequently light energy converts into the nerve impulses. These nerve impulses are transmitted by the optic nerve to the brain where they are processed and the result is perceived as an image [7].

Measuring different parts of the eye's temperature are common in the field of ophthalmology because any rise in temperature may indicate a kind of disease. Attempting to measure the temperature of the eye goes back to 1875. At that time, cornea's surface temperature was measured 36.5° by Dohnberg [8]. Efforts continued until 1960; the temperature through infrared radiation was measured with an instrument called Bolometer. This measurement is based on electrically conductive media where infrared light is radiated into the environment by which changes in the peripheral resistance is measured. Then, the resistance changes are converted into the temperature which is monitored on the screen and represents the eye temperature [8]. One of the first researches on corneal

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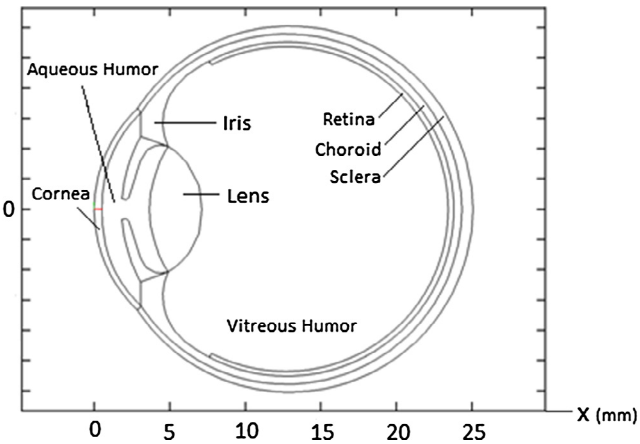

Fig. 1. The anatomy of the normal human eye with actual dimensions.

temperature change due to laser radiation was performed in 1979. During the initial investigation, the cornea has been modeled as one-dimensional slab and the temperature distribution has been determined for infrared radiation [9]. In 1999, the threshold value of argon fluoride laser's energy to remove the corneal surface was investigated. In this study, the cornea was hit by different laser light energy densities, and the threshold value was set to 30 mJ/cm^2 for cornea [10]. Eye problems treatment related to refraction of light such as myopia, hyperopia and astigmatism with laser was introduced in 1997 [11]. Since then, a lot of studies have been done on the damaging effects of heat on the eye's tissue. In [12], parts of the iris and sclera were considered as cellular and other parts of the cornea, aqueous humor, lens and vitreous were two-dimensionally modeled and analyzed by FEM method. Four different models were considered to study inner and outer temperature of the eye. The conditions of the external ambient temperature, blood temperature and heat transfer coefficient of blood in different parts of the eye were taken into account. Finally, it was found that aqueous humor and blood flow in the choroid of the eye play an important role in moderating temperatures. In [13], steady state temperature was determined using a three-dimensional model. In [14], the temperature around the eye pupil in steady state was investigated with or without considering the metabolism and blood flow to the retina and in [15] the impact of warm environments such as sauna was studied on the eye health and vision.

Sixty to seventy percent of light refraction in the eye is done by the cornea [16]. As Fig. 2 shows, in myopia or hyperopia, the cornea loses its normal shape and the beam of light is not properly focused on the retina to create a clear image. Therefore, ophthalmologists reshape the cornea surface by lasers to focus the beam of light again on the retina [11]. Two different kinds of lasers are used for corneal correction. The first one is the ArF laser with ultraviolet light radiation which is used for corneal reshape. The second one is Ho:YAG laser which is suitable for minimizing and shrinking the corneal surface. PRK, LASIK and LASEK (Laser Sub Epithelial Keratomileusis) are common ways to reshape the cornea.

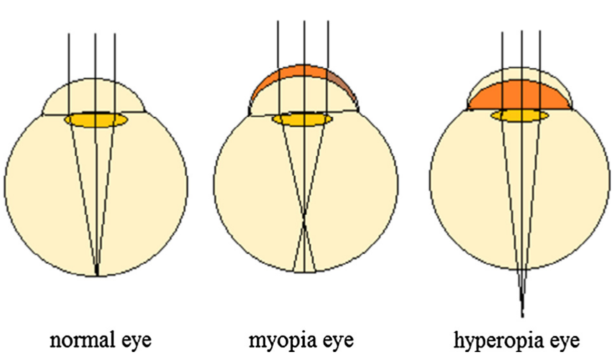

Fig. 2. Sketch of the normal, myopia and hyperopia eye.

Transmission, reflection, scattering and absorption are the fundamental parameters affecting the light propagation. Among these, light absorption is the most important phenomena because it can raise the temperature of the media [17]. Hence, one of the most important issues before the eye surgery is estimating the temperature of the eye. The best temperature is the one that could cause the most desired effect and the least unwanted destruction. For example, in surgeries dealing with corneal curve reshape, the desired minimum temperature for warming up the surface of the cornea is 64 °C [18]. Unwanted destruction is not reversible in laser eye surgeries and that is why using software and mathematical models are very important to predict the temperature of the eye before any kind of laser surgery. In [19], thermal effects and heat transfer of blinking has been studied using FEM where it has been shown that blinking increases corneal and lens temperature. Also, it has been discussed that this model can be used in eye cancer diagnosis by searching for eye tissues with drastic rise in temperature. The same approach is applied in [20] to investigate thermal effect of physiological parameters such as blood perfusion, porosity, evaporation and environment temperature on sclera and cornea. Moreover, the parabolic and hyperbolic models of Penn's general bio-heat equation are considered in [2] for analyzing heat temperature in cornea when exposed to high power ultra short pulsed laser. Then, these models have been solved by providing an analogy between the thermal and electrical systems using HSPICE program. Also, an experimental investigation (not mathematical) of thermal effects of laser irradiation on retina during photocoagulation by optical coherence tomography is studied [21].

In this paper we carry out a mathematical study, not in-vivo or ex-vivo study, on the linear thermal effects of human eye based on the Penn's bio-heat transfer equation. To this end, first, the governing Penn's bio-heat transfer equation is introduced. Next, the existing boundary conditions on the cornea and choroid representing the heat transfer from these layers to the adjacent layers are explained. Then, to study the thermal effects, eye is irradiated by a laser light (Gaussian beam) as an illuminating source. The absorption of this light by the eye tissues is considered to be linear. Using these boundary and illumination conditions, Penn's equation is numerically solved using finite element method and the results of the simulations are discussed. In addition, the heat transfer equation is semi-analytical solved in one-dimension and the results are presented in order to verify the simulation results. Finally, the outcomes of the present research are compared with the previous studies.

2. Methods and eye model

Since blood flow does not play a significant role in the thermal regulation process of the eye tissues, modeling and analyzing thermal effects of human eye is of great importance [22]. The heat distribution in the human eye's tissues is modeled based on the Penne's equation as follows [4]:

$$\rho_t c_t \frac{\partial T_t}{\partial t} = \nabla \cdot (k_t \nabla T_t) + \rho_b c_b w_b (T_b - T_t) + Q_m, \tag{1}$$

where ρ_t and ρ_b are the density of tissue and blood (kg/m^3), respectively. c_t and c_b also show thermal coefficient of tissue and blood ($J/kg \cdot K$). k_t presents tissue heat transfer coefficient (W/mK) and T_t is the temperature of tissue in Kelvin. t is time in second. w_b is

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