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Thermal behavior of human eye in relation with change in blood perfusion, porosity, evaporation and ambient temperature

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ABSTRACT

Extreme environmental and physiological conditions present challenges for thermal processes in body tissues including multi-layered human eye. A mathematical model has been formulated in this direction to study the thermal behavior of the human eye in relation with the change in blood perfusion, porosity, evaporation and environmental temperatures. In this study, a comprehensive thermal analysis has been performed on the multi-layered eye using Pennes' bio-heat equation with appropriate boundary and interface conditions. The variational finite element method and MATLAB software were used for the solution purpose and simulation of the results. The thermoregulatory effect due to blood perfusion rate, porosity, ambient temperature and evaporation at various regions of human eye was illustrated mathematically and graphically. The main applications of this model are associated with the medical sciences while performing laser therapy and other thermoregulatory investigation on human eye.

Contents

1. Introduction

The heat distribution in human eye is basically due to conduction, convection, evaporation, etc. The thermal stability of human eye is a subject of great concern due to its insufficient blood flow and lack of skin as a protecting layer. The physiology of the human eye operates the thermoregulatory mechanism up to large extent in various physiological and moderate ambient conditions; however, the severity of heat and cold cause adverse effects on its thermal equilibrium as demonstrated by Chuak et al. (2005). Such disturbances leads to damage the sensitive tissues of the human eye and thereby eye vision reported in Maryama and Kambiz (2011). Thus, it is imperative to study the role of physiological and environmental conditions on the thermal stability and other homeostasis of human eye. The information in this direction can be useful not only in clinical situations but can be helpful to

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maintain the heat distribution while performing laser surgeries and other medical diagnosis.

Eye is a multi-layered organ in the human body. In order to understand the thermal physiological model of human eye, it is necessary to understand the basic anatomy of eye. Cornea is the part of eye that is directly exposed to the radiations while as sclera is the only part having blood vessels and helps the eye in maintaining its temperature regulation with the other organs of body. The human eye is very flexible and hence any disturbance in thermal stability and to physiological changes including environmental disturbance is intolerable. Therefore, computational modeling of the thermoregulation in human eye is very important for estimating the temperature distribution at various adverse situations. A mathematical model can be helpful for the doctors in clinical situations in order to optimize their surgical protocol as discussed by Khanafer and Vafia (2009). Heat transfer models in the eye were developed by various researchers since last forty years. One of the earliest work was carried by Al-Badwaihy et al. (1976) to examine the thermal effects of microwave radiation on the human eye. The model discussed an analytical solution for the steady-state temperature distribution in which eye was modeled as a spherical structure with thermal parameters as the averaging of the thermal properties of the individual ocular tissues. Taflove and Brodwin (1976) studied the microwave radiations effect on the human eye and they obtained the transient solution using the finite difference method. In the previous existing models (Al-Badwaihy et al., 1976; Taflove and Brodwin, 1976), eye was considered as a homogeneous tissue with thermal parameters similar to that of water. The major drawback of their model was that the heat lost from the eye was considered due to constant convective heat transfer coefficient over the entire eye ball surface and as such it did not distinguish the heat transfer between the cornea and the environment, sclera and the body. Scott (1988) developed a mathematical model for human eye based on the bio-heat transfer equation and the results were established using finite element method. Chuak et al. (2005) developed a mathematical model for predicting the temperature distribution by making use of finite volume method within the human eye when subjected to a laser source. Ng and Ooi (2006) studied the three dimensional model for the human eye and compared the study with their work on two dimensional model. Khanday et al. (2014a, 2014b) studied heat distribution patterns using one dimensional transient heat equation together with FEM and Laplace transform techniques.

Due to the irregular geometries of the human tissues, the well known mathematical and ordinary numerical methods does not give the realistic values of temperature regulation in the human tissues as extensively discussed by Khanday and Najar (2015). However, variational finite element method provides an interesting aspect as compared to other numerical techniques for studying bio-heat transfer in the human tissues. In this paper, a mathematical model has been established to monitor the thermal instability in human eye in terms of changes in porosity, evaporation, perfusion rate and other environmental disturbances.

2. Model development

The governing equation used for modeling heat flow inside the biological tissues is based on Pennes' bio-heat equation (Pennes, 1948) which involves the role of conduction, metabolic heat generation and blood perfusion term. Since human eye is mainly comprised of water and therefore in few regions, the metabolic heat generation is playing negligible role for its temperature regulation. Blood perfusion term is dropped in the outer regions of the human eye while blood flow in sclera/iris plays a vital role in maintaining the eye temperature close to the other body organs.

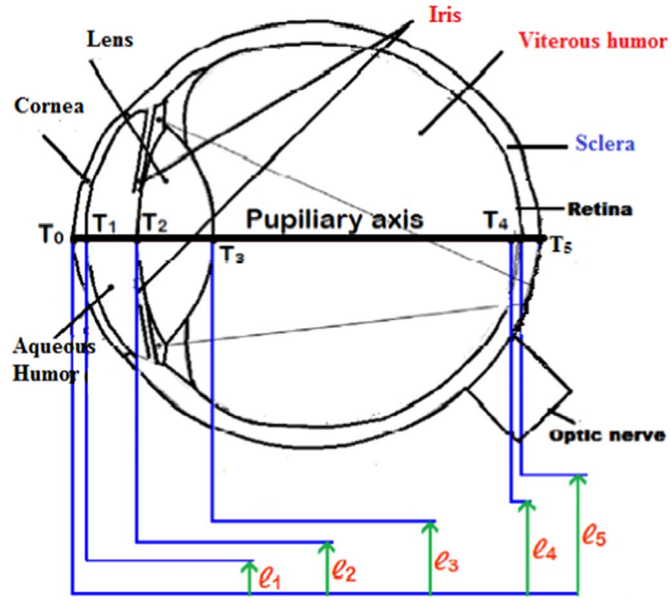

Fig. 1. Schematic diagram of human eye (Gokul et al., 2013).

This region is modeled as a porous medium and incorporating blood circulation through the tissue. Therefore, the modified Pennes' bio-heat equation has been used incorporated earlier by Nakayama and Kuwahara (2008) and Khanafer and Vafia (2009) is given as

$$(1-\phi)\rho c\frac{\partial T}{\partial t} = \nabla((1-\phi)k\nabla T) + \rho_b c_b \omega(T_b - T) + S \tag{1}$$

where k, T, t, S, ϕ, ω, ρ and c represents the thermal conductivity, temperature, time, metabolic heat generation, porosity, perfusion rate, density and specific heat of the tissues Fig. 1.

In order to make use of variational finite element method, the domain of the study is assumed to be consisting of sub-domains - cornea, aqueous humor, lens, viterous humor and sclera with the size of regions as l_1, $l_2 - l_1$, $l_3 - l_2$, $l_4 - l_3$ and $l_5 - l_4$ respectively. Also $T^{(0)}$, $T^{(1)}$, $T^{(2)}$, $T^{(3)}$ and $T^{(4)}$ represents the temperatures of the respective regions. Conduction is dominant heat transfer mechanism in cornea, aqueous humor, lens and vitreous humor parts of the eye and as such the Pennes' bio-heat equation for heat flow in these regions reduces to classical heat equation:

$$\rho_i c_i\frac{\partial T^{(i)}}{\partial t} = \nabla(k_i\nabla T^{(i)});\ \ (i = 0, 1, 2, 3) \tag{2}$$

Blood flow occurs in the sclera/iris region which we considered to be the porous media as such blood perfusion and porosity accounts for the heat transfer. The governing equation used for the heat transfer in the sclera region is given as

$$(1-\phi_4)\rho_4 c_4\frac{\partial T^{(4)}}{\partial t} = \nabla((1-\phi_4)k_i\nabla T^{(4)}) + \rho_b c_b\omega(T_b - T^{(4)}) \tag{3}$$

2.1. Boundary conditions

The thermal exchange between the eye and blood flow at the sclera occurs through convection and therefore the boundary condition at this interface is given by Newtons law of cooling

$$k\frac{\partial T}{\partial n} = h_b(T - T_b);\quad \text{at } x = l_5 \tag{4}$$

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