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Simulation of aqueous humor hydrodynamics in human eye heat transfer

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Abstract

The need to develop accurate representation of the human eye for the purpose of physiological studies is important to ensure that the predicted results are reliable. The presence of natural circulation of aqueous humor (AH) is evident from clinical, experimental and simulated observations. Most of the thermal models of the human eye that are found in the literature, however, had assumed a stagnant AH inside the anterior chamber. In this paper, a two-dimensional model of the human eye is developed where the circulation of AH inside the anterior chamber is included. The effects of the AH flow on the temperature distribution inside the eye are investigated. The natural circulation of AH is found to increase the temperature and distorts the temperature profile in the cornea and anterior chamber. Further investigations, where an artificial heat source is introduced inside the human eye suggest that AH flow plays a role in the heat transfer at the anterior region of the eye although this has yet to be quantified experimentally.

Keywords: Anterior chamber; Temperature; Aqueous humor; Human eye; Heat transfer

1. Introduction

Current method in ocular temperature measurement involves the use of infrared (IR) thermography which is non-contact and non-invasive. Although the non-invasive nature of IR thermography is advantageous over the more conventional contact thermometry, it however only allows the temperature on the corneal surface (tear film) to be recorded. This may not be advantageous in cases where information on the intraocular temperatures is vital such as during electromagnetic wave radiation [1–4] and during hyperthermic treatment of eye tumors [5,6].

In such situations, mathematical modeling may be used as an alternative since an eye model can be virtually dissected at any section for a thorough analysis on its temperature distribution. Eye models such as those developed by Lagendijk [5], Scott [7], Okuno [8] and Amara [9] were able to predict the ocular surface temperature to a reasonable accuracy when compared with experimental measurements in the literature. These models had assumed that the aqueous humor (AH) inside the anterior chamber is stagnant however. Despite the good agreement between the mathematical predictions and experimental measurements, it may be doubtful to conclude that the flow of AH inside the anterior chamber has no effect on the corneal temperature or any other location inside the human eye.

The models of the anterior chamber developed by Heys and Barocas [10], Kumar et al. [11] and Fitt and Gonzalez [12] had shown that the circulation of AH causes the temperature profile inside the eye to be unsymmetrical, which is different from those observed in the models by Scott [7], Okuno [8] and Amara [9]. Similarly, anterior chamber model by itself [10–12] provides no information on the effects of AH flow on the corneal surface temperature as well as the temperature distribution over the entire eye ball.

The present study is aimed at developing a two-dimensional model of the human eye which includes the presence of AH flow inside the anterior chamber. This allows qualitative investigations on the effects of AH flow on the temperature distribution inside the human eye to be carried out. The effects of different eye orientations on the AH flow and the temperature

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distribution are also investigated. The significance of AH flow in the human eye heat transfer is analyzed by placing an artificial heat source inside the human eye and the changes in temperature with time are observed.

2. Background of study

2.1. Mechanisms causing AH flow

Among the few mechanisms which are thought to be responsible for the circulation of AH flow are the constant replenishment of aqueous fluid from the trabecular meshwork [13], phakodenesis [12] and during rapid eye movement (REM) sleep [14]. Contributions from these factors to the flow of AH are, however, very small [11,12].

The replenishment of AH is well understood (see [16] and other related references therein). According to Ethier et al. [16], AH is produced at a rate of $\pm 2.4\,\mu\mathrm{l\,min}^{-1}$ (in adults) which corresponded to a turnover rate of 1% of the anterior chamber volume per minute. This value is considered to be too small to contribute to any leading order to the flow inside the anterior chamber [15,16].

Phakodenesis which describes the vibration of the human lens when the eye or the head moves is also suggested to be one of the cause of the AH circulation. Although numerical predictions are able to show the presence of AH flow due to phakodenesis, they remain inconclusive due to the lack of any form of experimental validation [12].

Aqueous mixing inside the anterior chamber during REM sleep was first proposed by Maurice [14]. It was proposed that during the closure of eyelids, the temperature inside the eye is maintained to be uniform everywhere. As a result, the driving force for the natural circulation of AH, i.e. the presence of temperature gradient is eliminated. Eventually, the stagnant AH prevents any oxygen supply to the cornea thus leading to corneal anoxia. Based on this hypothesis, Maurice [14] suggested that the purpose for the rapid movement of eyes during sleep is to produce AH mixing inside the anterior chamber in order to maintain a constant supply of oxygen to the cornea. A recent mathematical study by Fitt and Gonzalez [12], however, showed that movement of the human eye during REM sleep fails to produce any movement of aqueous fluid inside the anterior chamber since the AH will move together with the eye as one solid body.

The primary source of AH flow which has been generally agreed on is the thermally induced buoyant forces acting on the AH. This was first suggested by Türk in 1908 (cited by Canning et al. [15]). The buoyant forces are a result of the temperature difference between the front surface of the anterior chamber (generally at 34 °C) and the surfaces of the lens and iris which are assumed to be at 37 °C. The higher temperature at the surfaces of the lens and iris causes the temperature of the AH around it to increase. The warmer fluid which has a lesser density will tend to rise. At the front surface of the anterior chamber, the cooler fluid which has a larger density will descend. Consequently, a constant circulation of AH is generated inside the anterior chamber as long as the temperature gradient is present across it. It was found that a temperature as low as 0.02 °C is sufficient to induce circulation on the AH [11].

2.2. Model development

A two-dimensional model of the human eye which follows closely that in [17] is developed. Internal eye structures such as the anterior chamber, posterior chamber, iris, lens and vitreous are modeled based on the anatomical measurements found in the literature [18–20]. The model of the human eye is illustrated in Fig. 1 which consists of six major eye components namely the cornea, the anterior chamber, the posterior chamber, the lens, the vitreous and the sclera.

In the actual eye, beneath the layer of sclera, there exist two more layers known as the choroid and retina which are relatively thin compared to the sclera. For simplicity, we have modeled these layers together with the sclera as one homogeneous region. The iris which has properties similar to that of the sclera and the optic nerve is also modeled together with the sclera as one homogeneous region [21].

Thermal properties for each region of the human eye may be found in the literature and they are given in Table 1. Each region is assumed to be homogeneous and thermally isotropic.

2.3. Governing equations

In the present model, the motion of fluid is only considered inside the anterior chamber. Flows inside the posterior chamber and the vitreous are neglected [10–12,18,22]. By neglecting the metabolic heat and the effects of blood perfusion inside the eye, the equation governing the flow of heat may be written as

$$\rho_i c_i \frac{\partial T_i}{\partial t} = \nabla(k_i \nabla T_i), \tag{1}$$

where i denotes each region such as given in Table 1, T is temperature and t is time ($\partial T_i/\partial t = 0$ for steady state cases), respectively. Since the human eye is modeled as an organ which is isolated from the human head, the effects of blood flow in the choroid may be accounted in the boundary condition at Γ_2. More details are given in Section 3.

The Navier–Stokes equation is used to simulate the motion of AH inside the anterior chamber. In the x and y directions, respectively, they are given as [11]

$$\rho_i \left(\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x} + v_i \frac{\partial u_i}{\partial y} \right) = -\frac{\partial p_i}{\partial x} + \mu_i \left(\frac{\partial^2 u_i}{\partial x^2} + \frac{\partial^2 u_i}{\partial y^2} \right) + \rho_i g_x \tag{2}$$

and

$$\rho_i \left(\frac{\partial v_i}{\partial t} + u_i \frac{\partial v_i}{\partial x} + v_i \frac{\partial v_i}{\partial y} \right) = -\frac{\partial p_i}{\partial y} + \mu_i \left(\frac{\partial^2 v_i}{\partial x^2} + \frac{\partial^2 v_i}{\partial y^2} \right) + \rho_i g_y, \tag{3}$$

where u and v are velocities in the x and y directions, respectively, p is pressure and μ is the dynamic viscosity of AH.