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# Effects of aqueous humor hydrodynamics on human eye heat transfer under external heat sources

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ABSTRACT

The majority of the eye models developed in the late 90s and early 00s considers only heat conduction inside the eye. This assumption is not entirely correct, since the anterior and posterior chambers are filled aqueous humor (AH) that is constantly in motion due to thermally-induced buoyancy. In this paper, a three-dimensional model of the human eye is developed to investigate the effects AH hydrodynamics have on the human eye temperature under exposure to external heat sources. If the effects of AH flow are negligible, then future models can be developed without taking them into account, thus simplifying the modeling process. Two types of external thermal loads are considered; volumetric and surface irradiation. Results showed that heat convection due to AH flow contributes to nearly 95% of the total heat flow inside the anterior chamber. Moreover, the circulation inside the anterior chamber can cause an upward shift of the location of hotspot. This can have significant consequences to our understanding of heat-induced cataractogenesis.



## 1. Introduction

One of the difficulties in measuring intraocular temperature is the intolerance of the eye to physical contact. Consequently, the majority of the experimental studies carried out on ocular heat transfer have been restricted to in vivo and ex vivo animal studies [1–3], and donor human eyes obtained postmortem [4]; both of which do not accurately represent the physiological conditions of the living human. Measurements carried out using infrared (IR) thermography have also been reported in the literature [5–7]. Although non-invasive, this technique can measure only the temperature across the corneal surface. This becomes problematic when information on the intraocular temperature is of particular interest, such as when the eye is exposed to heat sources that raises its temperature from the inside. In an effort to gain a better understanding, some researchers have developed computational models to simulate the ocular heat transfer process across the entire eye. Numerous models that investigated a variety of heat transfer problems have been reported in the literature. A detailed review on the different approaches to modeling ocular heat transfer is given by Ooi and Ng [8].

Most of the human eye models reported in the literature assume heat conduction to be the only mode of heat transfer inside the eye [8–14]. This assumption ignores the flow of aqueous humor (AH); a watery substance that resides within the anterior and posterior chambers. AH flow is primarily caused by thermally-induced buoyant forces and this induces natural convection that may affect the overall heat transfer phenomena inside the eye. Studies carried out by Ooi and Ng [15] and Karampatzakis and Samaras [16] have shown that models that take into account the natural convection phenomenon produce corneal surface temperature profiles that are asymmetrical about the geometrical center of the cornea. The temperature along the pupillary axis around the anterior segment of the eye is also increased.

Nevertheless, the investigations carried out by Ooi and Ng [15] and Karampatzakis and Samaras [16] were confined to the case of an eye under normal thermophysiological conditions. To the authors' knowledge, there have been only a few eye models with AH flow that investigated how the eye temperature changes under external thermal loading. Papaiaonnou and Samaras [17] developed a model of the rabbit eye anterior chamber and coupled both the thermal and fluid dynamics modeling to investigate the thermal-fluid interaction when exposed to millimeter wave radiation. The same investigation was later extended by Karampatzakis and Samaras [18] using a three-dimensional model of the human eye for exposure to 40–100 GHz mm wave radiation. In a series of studies, Wessapan and Rattanadecho [19–22] investigated the

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elevation in the ocular temperature when exposed to electromagnetic (EM) waves using a two-dimensional model. A similar study was carried out to look at the ocular temperature distribution during sauna therapy [23]. Although the models took into account the effects of AH flow, they were developed in two-dimensions, which do not fully represent the anatomical structure of the human eye. Furthermore, no comparisons were made on the predictions obtained between the models with and without AH flow.

In this study, we aim to expand on the knowledge of the role of AH hydrodynamics on ocular heat transfer when subjected to external heat sources. Three-dimensional models of the human eye are developed for this purpose. The external heat sources are implemented based on information retrieved from the literature. Two types of heat sources are considered, namely exposure to ultra high frequency EM waves (750 MHz and 1.5 GHz) and surface heating due to IR irradiation. Simulations are carried out using the commercial software COMSOL Multiphysics®. Validation of the developed model is carried out by comparing the obtained predictions with their experimental and simulation counterparts reported in the literature.

## 2. Mathematical model

### 2.1. The human eye model

The model of the human eye is constructed based on the dimensions of the eye model reported by Ooi and Ng [15]. The model comprises seven domains, namely the cornea ($R_1$), the anterior chamber ($R_2$), the iris ($R_3$), the posterior chamber ($R_4$), the sclera ($R_5$), the vitreous ($R_6$) and the lens ($R_7$). The retina and the choroid are modeled together with the sclera as one homogeneous region due to their very thin structures. Fig. 1a shows the top half of the two-dimensional eye model in the sagittal plane. The three-dimensional model is obtained by rotating the planar model 180° about the pupillary axis. This is shown in Fig. 1b. In order to reduce the requirement for computer memory, only one-half of the model is developed by taking into account the symmetrical features of the geometry about the sagittal plane.

### 2.2. Governing equations

#### 2.2.1. Heat conduction

Except for the anterior chamber, the primary mode of heat transfer inside the eye is via conduction. For a biological medium, the heat transfer can be described using the Pennes bioheat equation [24]:

$$\rho c\frac{\partial T}{\partial t} = k\nabla^2 T + \rho_b c_b \omega (T_b - T) + Q_m + Q_{ext}, \quad (1)$$

where $T$ is temperature, $t$ is time, $\rho$, $c$ and $k$ are the density, specific heat and thermal conductivity of the tissue, respectively, $\omega$ is the blood perfusion rate of tissue, $Q_m$ is the volumetric heat generation due to tissue metabolism and $Q_{ext}$ is the volumetric heat absorbed by the tissue due to external heat source. The subscript $b$ in Eq. (1) represents blood. The thermal effects due to blood perfusion (second term on right hand side of Eq. (1)) is active only in the region defined by the sclera (retina + choroid) and the iris. Following the work of Lagendijk [9], the thermal effects due to blood flow inside the retina and the choroid may be modeled as part of the boundary condition prescribed across the scleroid surface. Since blood flow inside the iris is relatively smaller than the blood flow inside the choroid [25], its effects on the overall ocular heat transfer can be ignored. Metabolic heat generation inside the eye is also neglected since the majority of the components of the eye is avascular. Following these assumptions, the bioheat equation reduces to the classical heat diffusion equation:

$$\rho_i c_i \frac{\partial T_i}{\partial t} = k\nabla_i^2 T_i + Q_{ext}, \quad \text{for } i = 1, 3, 4, 5, 6 \text{ and } 7, \quad (2)$$

where the indices refer to the notation depicted in Fig. 1a.

#### 2.2.2. Heat convection

Heat transfer due to natural convection inside the anterior chamber can be described using:

$$\rho_i c_i \frac{\partial T_i}{\partial t} + \mathbf{v}\cdot\nabla T_i = k_i \nabla^2 T_i + Q_{ext}, \quad \text{for } i = 2 \quad (3)$$

where $\mathbf{v}$ is the velocity vector of the AH flow. Eq. (3) above follows the assumptions made in Section 2.2.1, where the blood perfusion and metabolic heat generation terms are ignored due to the anterior chamber being an avascular region.

#### 2.2.3. Flow field

The flow of AH inside the anterior chamber can be described using the Navier-Stokes equations, which consist of the momentum (Eq. (4)) and the continuity equations (Eq. (5)):

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \mu\nabla^2\mathbf{v} + \mathbf{F}, \quad (4)$$

$$\nabla\cdot\mathbf{v} = 0, \quad (5)$$

where $p$ is pressure, $\mu$ is the dynamic viscosity of AH and $\mathbf{F}$ is the thermally-driven buoyant forces that can be described using the Boussinesq approximation:

$$\mathbf{F} = \rho\mathbf{g}\beta(T - T_{ref}), \quad (6)$$

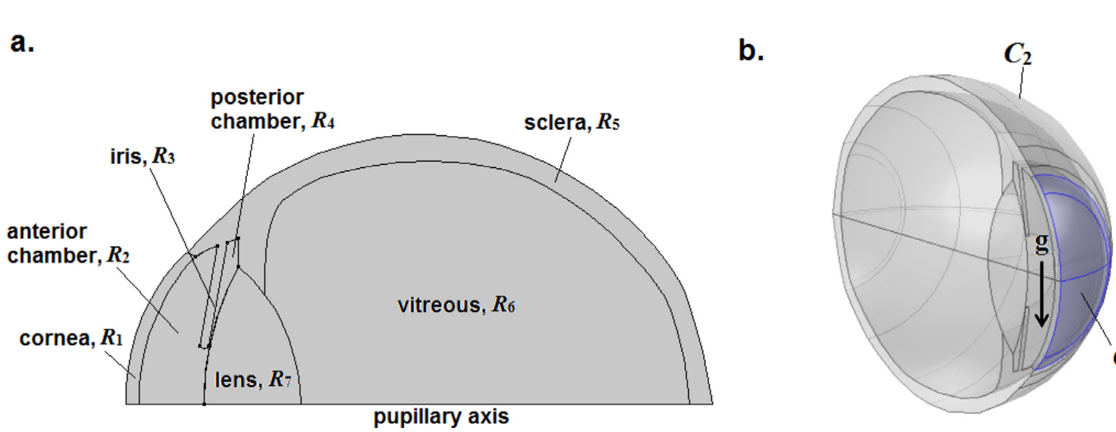


**Fig. 1.** The human eye model in (a) two-dimensional sagittal plane and (b) three-dimension.