Human Eye Imaging and Modeling

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CRC Press
Taylor & Francis Group
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Symbols

$k$ Thermal conductivity of tissue (W·m$^{-1}$·K$^{-1}$)
$\rho$ Density of tissue (kg·m$^{-3}$)
$c$ Specific heat of tissue (J·kg$^{-1}$·K$^{-1}$)
$T$ Temperature of tissue (K)
$t$ Time (s)
$a_b$ Blood perfusion rate (m$^3$·s$^{-1}$·ml$^{-1}$)
$\rho_b$ Density of blood (kg·m$^{-3}$)
$C_b$ Specific heat of blood (J·kg$^{-1}$·K$^{-1}$)
$T_a$ Artery temperature (K)
$h_m$ Film coefficient of ambient fluid (W·m$^{-2}$·K$^{-1}$)
$T_m$ Sink temperature of ambient fluid (K)
15.1 INTRODUCTION

The prediction of bioheat transport in a biological system is of importance in many diagnostic and therapeutic applications. However, analytical prediction is usually difficult in practice because some biological tissues, such as those in the human eye, have different physical properties and domains with complex geometries. The application of computational methods in modeling biological systems has thus attracted increasing attention, benefiting from the rapid development of computer science.

Among the numerical methods developed to date, the finite element method (FEM) and boundary element techniques have been widely used to analyze bioheat transfer phenomena in the human eye. For example, finite element (FE) models in cylindrical coordinates and rectangular coordinates for two-dimensional human eye structures were developed by Scott (1988) and Ng and Ooi (2006), respectively. The former is based on the assumption that the human eye is symmetric about the pupillary axis, ignoring the optic nerve region. The latter uses the commercialized software FEMLAB 3.1 as the computing tool. By considering the circulation of aqueous humor, Ooi and Ng (2008) utilized the FE technique to conduct heat transfer analysis for two-dimensional eye problems. A cylindrical eye model based on the FEM was also developed by Brinkmann et al. (1994). In the FEM analysis mentioned above the solution domain is divided into several cells or elements with independent material definition, and in each subdomain the physical fields are approximated by appropriate polynomial interpolations. A weak-form integral functional is developed to produce the final stiffness equations. The finite volume method (FVM) (Chua et al. 2005; Narasimhan, Jha, and Gopal 2010) and the finite difference method (FDM) (Mainster, White, and Tips 1970) have also been employed to study transient temperature changes in the human eye caused by responses to a laser source.

Besides the domain-type methods mentioned above, the boundary element method (BEM) or dual reciprocity BEM (DRBEM) involving boundary integrals only have been applied to numerical thermal analysis in human eye structures (Ooi, Ang, and Ng 2007; Ooi, Ang, and Ng 2008; Ooi, Ang, and Ng 2009; Peratta 2008). Unlike the FEM, FVM, and FDM, in the BEM analysis the time-consuming domain integrals appearing in the FEM are replaced with boundary integrals (one dimension is reduced) via the use of Green's functions. However, the treatment of singular or near-singular boundary integrals is usually quite tedious and inefficient, and an extra boundary integral equation is also required to evaluate the interior fields within the domain. Moreover, for multidomain problems, the BEM establishes the boundary integral equation separately for each subdomain, and complementary equations associated with the continuity conditions on the interface of adjacent subdomains are required. As a result, evaluation of the coefficient matrix of the resulting equations becomes complex. To overcome this problem, a new type of Green's-function-based approach, a hybrid FE model containing non-singular elementary boundary integrals only, was established for heat transfer in the eyeball, and the corresponding iterative algorithm was constructed for the treatment of nonlinear radiation conditions (Wang and Qin 2010). The developed hybrid FE model, referred to as HFS-FEM, displays the advantages of both FEM and BEM.

The studies discussed above have not considered the blood perfusion rate in the eyeball, and thus in their analyses the Pennes bioheat equation could be reduced to the conventional heat conduction equation. In practice, blood perfusion activity exists in local regions of the eyeball (Flyckt, Raaymakers, and Lagendijk 2006), and accurate prediction of the temperature distribution in the eye then depends on how the impact of the blood flow is taken into account. In this study, evaluation of the transient temperature distribution in a two-dimensional eyeball is performed using FE analysis, taking into account the blood perfusion effect in the sclera, the choroid, retina layers, and the optic nerve, based on the classic Pennes bioheat equation. The thermal properties and control parameters in the computation are chosen from the literature, and the predicted thermal variation in the eyeball is verified by comparison with available results from previous studies of human as well as animal eyes.

15.2 MATHEMATICAL MODEL

The human eyeball is a very complex biological system. Figure 15.1 shows a schematic diagram of the physiology of the human eye, from which it can be seen that the eye is an approximately spherical organ. The anterior transparent surface of the eye is the cornea. The lens lies in between the aqueous humor and vitreous humor, which are transparent liquids of different concentrations. The sclera is the outer white coat that provides full protection to the eye. Besides the cornea, iris, aqueous humor, sclera, vitreous humor, and optic nerve, there are two layers of tissues falling in between the sclera and the vitreous humor, namely the retina and the choroid. The retina is permeated with blood vessels and is connected to the brain by the optic nerve. Under the retina the choroid serves to nourish it.

Abstracting from Figure 15.1, a typical two-dimensional mathematical model of the human eye as sketched in Figure 15.2 is taken into consideration for the following computation. In the figure, only cornea, iris, aqueous humor, sclera, vitreous humor, and optic nerve are considered. For simplicity, since the retina and choroid layers are relatively thin, they are modeled together with the sclera and the optic nerve. Moreover, for the sake of convenience, each of the subdomains is assumed to be thermally isotropic and homogeneous.

Exact discrimination between the aqueous and vitreous humors is not possible, nor between the iris and the ciliary body. Because they are water-like, their physical properties are approximately equivalent. Convection of the aqueous humor is not modeled since it is assumed to have a negligible effect on the resulting temperature distribution.

Referring to the rectangular coordinate system \((x,y)\) with the origin at the center of the outer surface of the cornea and the arrangement of the horizontal axis coinciding with the papillary axis, the governing equation representing the bioheat transfer
in the eyeball domain $\Omega$ can be written using the well-known Pennes bioheat equation, which addresses the effect of blood perfusion and metabolic activities in the biological system (Pennes 1948):

$$k \nabla^2 T + \rho c_b w_b (T_o - T) + Q_m + Q_e = \rho c_b \frac{\partial T}{\partial t} \quad \text{in } \Omega \quad (15.1)$$

where $\nabla^2 = \partial^2 / \partial x^2 + \partial^2 / \partial y^2$ denotes the Laplace operator, $t$ is the time variable, $\rho$ represents the density of the tissue, $c_b$ stands for the specific heat of the tissue and $k$ is the thermal conductivity of the tissue, $w_b$ is the blood flow rate, that is, the volume of blood flowing through a unit mass of tissue per unit time, $\rho_b$ is the density of blood, $c_b$ is the specific heat of the blood, $T_o$ represents the unknown tissue temperature, $T_i$ denotes the blood temperature, $Q_m$ stands for the metabolic heat source term, and $Q_e$ represents the external heat generation, which may be caused by an external laser beam, electrical disturbance, radiation of electromagnetic waves, and so on. The relevant thermal properties including thermal conductivity, specific heat and density for the different subdomains are tabulated in Table 15.1, based on data from the literature (Flyckt, Raaymakers, and Lagendijk 2006; Narasimhan, Jha, and Gopal 2010; Ooi, Ang, and Ng 2009; Ng and Ooi 2006).

In addition, the following boundary conditions and initial condition are added to the biological system.

### 15.2.1 Convection, Radiation, and Tear Evaporation on the Corneal Surface $\Gamma_1$

Since the cornea is the only region in the eye that is exposed to the environment, the heat loss caused by convection and radiation should be considered. Also, the evaporation of tears on the corneal surface increases its cooling rate. The three forms of cooling mechanism can be combined and the related boundary condition on the surface of cornea is written as

<table>
<thead>
<tr>
<th>Subdomains</th>
<th>$k$ (W-m$^{-1}$K$^{-1}$)</th>
<th>$c_b$ (J-kg$^{-1}$K$^{-1}$)</th>
<th>$\rho$ (kg-m$^{-3}$)</th>
<th>$\omega_b$ (mL$^{-1}$-s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornea</td>
<td>0.58</td>
<td>4178</td>
<td>1050</td>
<td>0</td>
</tr>
<tr>
<td>Aqueous humor</td>
<td>0.58</td>
<td>3997</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Iris</td>
<td>1.0042</td>
<td>3180</td>
<td>1100</td>
<td>0</td>
</tr>
<tr>
<td>Sclera/retina/choroid</td>
<td>1.0042</td>
<td>4178</td>
<td>1000</td>
<td>0.02219</td>
</tr>
<tr>
<td>Lens</td>
<td>0.40</td>
<td>3000</td>
<td>1050</td>
<td>0</td>
</tr>
<tr>
<td>Vitreous body</td>
<td>0.603</td>
<td>4178</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>Optic nerve</td>
<td>1.0042</td>
<td>3680</td>
<td>1030</td>
<td>0.00371</td>
</tr>
<tr>
<td>Blood</td>
<td>0.53</td>
<td>3600</td>
<td>1050</td>
<td></td>
</tr>
</tbody>
</table>

Source: Flyckt, Raaymakers, and Lagendijk 2006; Narasimhan, Jha, and Gopal 2010; Ooi, Ang, and Ng 2009; Ng and Ooi 2006.
solving complex partial differential equations (PDEs), based on the MATLAB PDE toolbox. It should be mentioned that the geometrical dimensions of the computational model employed in this study are taken from the geometrical dimensions of the ribbed flue, which is the only difference in the computational model here. The geometrical dimensions and the computational model used for this study are based on the geometrical dimensions and the computational model used for the previous study.

To simulate the temperature distribution in the ribbed flue, the values of control parameters related to the outer boundary conditions are listed in Table 15.2 (Ooi, Ang, and Ng 2007; Ng and Ooi 2006) for consideration.

### Table 15.2 Control Parameters Related to Boundary Conditions

<table>
<thead>
<tr>
<th>Control Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood temperature $T_b$</td>
<td>37°C</td>
</tr>
<tr>
<td>Blood temperature coefficient $h_b$</td>
<td>65 (W/m²K)</td>
</tr>
<tr>
<td>Ambient temperature $T_a$</td>
<td>0–50°C</td>
</tr>
<tr>
<td>Ambient temperature coefficient $h_a$</td>
<td>10–100 (W/m²K)</td>
</tr>
<tr>
<td>Corrosa surface emissivity $\varepsilon$</td>
<td>0.975</td>
</tr>
<tr>
<td>Evaporation rate of water $\rho_w$</td>
<td>40–320 (W/m²)</td>
</tr>
</tbody>
</table>

#### Figure 15.3 Triangular finite element mesh for two-dimensional human eye model

#### 15.3 Numerical Experiments

FEM is regarded as an appropriate tool for simulating thermal effects in the eye model, which usually consists of several regions. Thermal analysis of biological tissues using FEM can be categorized as a nonstructural solution using finite element analysis software packages that are tailored for structural analysis. The model is then imported into AUTOMATIC software to generate a graphics image in the eye. Subsequently, the images are imported into MATLAB 3.2 (COMSOL Inc., Burlington, MA), which is suitable for...
between adjacent refinement levels. The ambient temperature is specified as 25°C, the ambient convection coefficient is assumed to be 10 Wm⁻²K⁻¹, the loss of heat flux \( E_0 = 40 \text{ W/m}^2 \), the initial temperature \( T_0 = 0^\circ \text{C} \) (Paruch 2007), and the time step is chosen as \( \Delta t = 2 \text{ s} \). A relatively steady state is achieved when the inter-iteration difference between adjacent time instances is less than or equal to a small value (i.e., 10⁻²). It is necessary to mention that the initial temperature does not affect the final steady state of the temperature distribution, but it can affect the time taken to a steady state heat transfer and can change the manner of heat transfer at the start time.

The heating effect of blood perfusion in the sclera and optic nerve is initially ignored for the purpose of comparison with available experimental and numerical results. At this time, the governing equation (15.1) of the bioheat transfer is reduced to a standard transient Poisson equation. At the time instant \( t = 2970 \text{ s} \) a relatively steady state is achieved. The temperature at the center of the outer corneal surface is 34.135°C, which is within the temperature range (from 33.4°C to 34.8°C) presented in Table 3 of Ooi, Ang, and Ng (2007). The calculated value has a percentage relative error 0.87% with 34.435°C obtained using the HFS-FEM (Wang and Qin 2010). In Figure 15.4 the temperature distribution in a human eye for the time at 10, 100, 1000, and 2700 s is presented, and good agreement is observed with results from Paruch (2007). It can be seen from Figure 15.4 that the region with lower temperature associated with the initial temperature becomes smaller as time progresses, and then the heat transfer behavior due to the temperature difference between the ambient fluid outside the cornea and the blood flow outside the sclera dominates. In the absence of blood perfusion, the distribution of temperature along the papillary axis is plotted in Figure 15.5. As expected, at \( t = 2970 \text{ s} \), good agreement is achieved between the current results and those from the HFS-FEM. The temperature on the papillary axis is observed to increase from 34.135°C at the center of the outer corneal surface to 36.618°C at the intersection point of the outer surface of sclera and the horizontal coordinate axis. Simultaneously, the change of heat conduction behavior is clearly illustrated as time progresses. Thus, the computing model presented allows us to obtain a relatively accurate result for the temperature distribution of a human eye and is therefore verified.

15.3.2 Effect of Blood Perfusion Rate

In the analysis of the thermal effects of blood perfusion rate, the value in the literature (Flyckt, Raaymakers, and Lagendijk 2006) is taken into consideration as the control parameter for investigation purposes. This enables us to understand the importance of blood flow in the thermoregulation of the human eye. The effects of blood perfusion on the transient temperature distribution inside the human eye, both at the center of the corneal surface and along the papillary axis, are displayed in Figures 15.6–15.8. It is found from Figure 15.6 that the presence of blood perfusion in parts of the sclera and optic nerve makes the heat transfer more rapidly in the eyeball compared to the case without blood perfusion. Because the blood temperature, which is 37°C here, is the highest in the computing domain, a heating effect rather than a cooling effect takes place, and more heat energy flows from the blood vessels in the sclera region into the eyeball to cause a temperature increase. Figure 15.7 shows the transient temperature variation at the center of the outer corneal surface. We find that a steady
The results obtained from this analysis imply that the blood flow in the eye plays an important role in the overall temperature distribution in the eyeball.

### 15.3.3 Effect of Ambient Fluids

The thermal effect of ambient fluid near the outer corneal surface can be analyzed by changing two parameters: ambient temperature and ambient convection coefficient. In the present work, the value of the ambient temperature is restricted to within the range 0–50°C and the ambient convection coefficient is chosen in the range 10–100 W m\(^{-2}\) K\(^{-1}\) to study the induced temperature response. The evaporation rate is assumed to be 40 W m\(^{-2}\) in the computation. The related numerical results are presented in Figure 15.9 and Figure 15.10. In Figure 15.9, the ambient temperature changes and the convection coefficient of the ambient fluid remains at 10 W m\(^{-2}\) K\(^{-1}\). It can be seen from Figure 15.9 that a significant increase in the temperature at the center of the corneal surface can be detected when the ambient temperature increases from 0°C, 25°C to 50°C, each level corresponding to cold, moderate, and extremely hot conditions, respectively. The higher sink temperature allows more heat to flow into the eye and causes a higher corneal surface temperature. In the final steady state, about 31°C at the sample point is observed for every increment of 25°C in the ambient temperature. In Figure 15.10, the variation of the convection coefficient is investigated with a sink temperature of \(T_s = 25°C\). As expected, we find that the higher value of the convection coefficient of ambient fluid first causes more rapid heating on the corneal surface when \(t < 420 \text{ s}\). It is understandable that in this stage the heat energy flows from the surrounding fluid to the corneal region and the corneal temperature is below 25°C, the sink temperature. Then the higher convection coefficient leads to more heat loss (cooling effect) when \(t > 420 \text{ s}\), and the corresponding steady state temperature is lower, since the corneal surface temperature exceeds the ambient temperature at this stage, and the heat energy flow is reversed.
FIGURE 15.6 Transient temperature distribution in the human eye with specified blood perfusion.

(Continued)
FIGURE 15.7 Transient temperature variation at the center of the corneal surface for two different cases.

FIGURE 15.8 Steady temperature variation on the papillary axis for two different cases.

FIGURE 15.9 Temperature variation at the center of the cornea for various ambient temperatures.

FIGURE 15.10 Temperature variation at the center of the cornea for various ambient fluids.
15.3.4 Effect of Tear Evaporation

There is usually a thin lipid layer covering the corneal surface, the function of which is to prevent evaporation of tears from the corneal surface. When the layer is destroyed, the evaporation rate increases dramatically and can reach as high as 320 Wm⁻² (Mishima and Maurice 1961), whereas the evaporation rate of normal eyes is in the range of 20–100 Wm⁻² (Scott 1988). It is therefore important to investigate the effect of evaporation on temperature distribution in the eye model. In the following analysis, the temperature and the convection coefficient of ambient fluid are taken to be 25°C and 10 Wm⁻²K⁻¹, respectively. The temperature variation at the center of the corneal surface is shown in Figure 15.11, from which it can be seen that the evaporation rate seems to be important in changing the corneal surface temperature. The larger the value of the tear evaporation, the lower is the temperature at the center of the corneal surface. It is understandable that the cooling effect increases as the evaporation rate increases. It is also observed from Figure 15.11 that there is an approximately steady decrease in the value of 0.125°C at the center of the corneal surface for every increment in the value of 10 Wm⁻² for evaporation rate.

15.4 Conclusions

In this chapter, a transient FEM model is constructed to perform computer simulation of the thermal states of biological bodies governed by the Pennes bioheat equation. The purpose of this chapter is to investigate the thermal effect in the eyeball caused by blood perfusion rates in the sclera and the optic nerve. It is shown that the eye is very difficult to heat or cool when physiological perfusion is correctly taken into account. Validation of the transient mathematical model including blood perfusion in the eye was performed by comparing the findings with results in the literature. Subsequently, through sensitivity analysis conducted in the presence of blood perfusion in the eyeball, three dominant parameters (ambient temperature, film coefficient of ambient fluid, and tear evaporation rate) were determined, to obtain insight and to weight the importance of each parameter. These parameters significantly affect the surface temperature of the cornea in practice.

ACKNOWLEDGMENT

The work reported in this chapter is partially supported by the Australian Endeavor Awards 2011 and Foundation for University Key Teacher by the Henan Province, China, under the grant no. 2011GGJS-083.

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**16 Modeling and Simulation of Bioheat Transfer in the Human Eye with Edge-Based Smoothed Finite Element Method (ES-FEM)**

*Eric Li, GR Liu, Vincent Tan, and ZC He*

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