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Using a two-Dimensional Finite Element Model to Simulate Biothermal Transfer in the Human Eye) by Considering the Rate of Tear Evaporation and Radiation to the Eye Surface)

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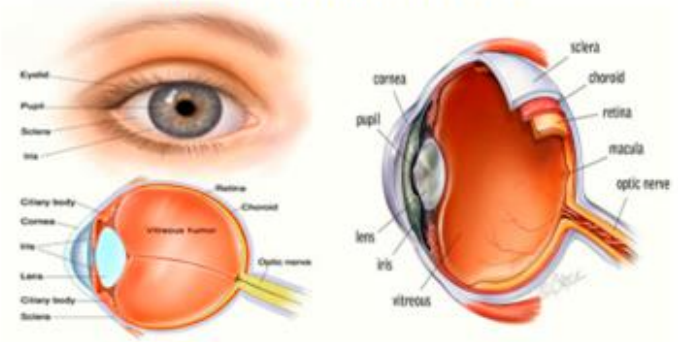
ABSTRACT

Thermal simulation of the human eyeball has been considered in recent years to investigate the effect of external heat sources as well as to predict ocular abnormalities and vital vision disorders. Due to the advances in the field of computing technologies, the use of computer simulation methods such as the use of simulation software and also the use of that software in areas such as medical sciences have received much attention, so that the results have been very helpful in diagnosing various eye diseases and inflammations in the medical community. In the present study, a two-dimensional finite element model has been used to simulate the transfer of biothermal heat in the human eye at steady state. In this study, COMSOL Multiphysics 4.4 software was used to simulate heat transfer in the human eye at steady state. The results of this modeling were compared by examining the effective parameters such as the effect of ambient temperature, blood temperature, lens conduction coefficient, blood transfer heat transfer coefficient, corneal surface diffusion coefficient and the effect of tear evaporation rate. Ocular inflammation is the strongest factor and also the impossibility of ignoring the amount of eye radiation with the environment and the effect of this factor on a significant increase or decrease in corneal surface temperature.

GRAPHICAL ABSTRACT



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Introduction

Due to the advances in the field of computational technologies, the use of computer simulation methods such as the use of simulation software and also the use of that software in areas such as medical sciences have received much attention, so that the results of it have been used extensively in the diagnosis of various diseases with the help of the medical community, for example, we can mention the modeling of heat transfer in the human eye. Heat transfer and temperature distribution profile in ocular tissue have been highly regarded in the last hundred years [1]. The eye is a sensitive organ of the human body that disorders or even a small change in its internal temperature can be harmful to this organ. In addition, temperature changes in the eyeball during laser surgery or when working with harmful heat sources such as arc welding or while working with a furnace are very important for analysis. Therefore, studying the temperature characteristics of the eye in order to diagnose primary abnormalities in the eye, designing a mechanism to protect the eye and prevent its damage is vital [3].

On the other hand, we know that the eye is a living organ and, like other organs in the body, energy is transferred to this organ through the bloodstream. However, due to the visual function of this organ, the ocular arteries are present only in the choroidal region. In addition, it is assumed that metabolic heat production in ocular tissues is negligible. The only heat source considered is the transfer heat transfer due to blood flow under normal conditions, which is assumed as an external heat source [20].

Eye diseases, which are the main cause of blindness, are often diagnosed too late, which can lead to disease progression and blindness. Therefore, such diseases can be prevented with early diagnosis. To achieve this, we can use artificial intelligence algorithms and other computer software that help simulate and model existing problems, and thus take a step towards early diagnosis of diseases and help treat them. In general, it can be said that biochemical processes depend on temperature, the transfer of heat plays a major role in the system of the kidneys. Heat transfer is influenced by vascular geometry, local blood flow rate, and blood heat capacity [13]. The blood temperatures of the arteries and veins may be different and sometimes the same for the temperature of their local tissue.

These temperatures change with many unstable physical and physiological parameters, as temperature and blood flow are critical factors that underlie bioengineering in understanding, molecular manipulation, and the biochemical processes that underlie life. Research shows that the approximate rate of all physiological functions varies between 6 and 10% per degree Celsius [2]. In general, the aim of the present study was to investigate the biothermal transfer in the human eye by using COMSOL Multiphysics 4.4 software. An attempt has been made to use a reliable two-dimensional model and biothermal transfer in the above-mentioned software to solve this problem. Then, according to the modeling results, the effect of parameters such as ambient temperature, blood temperature, lens conduction coefficient, the effect of heat transfer on blood circulation, the effect of corneal diffusion coefficient and also the effect of tear evaporation rate on eye temperature. In this article, we have tried to use Kamsol separation software instead of other common software such as Fluent, which was present in most of the researched studies.

In the present study, the effect of these two parameters on heat transfer could be investigated by examining the effect of mass transfer coefficient and tear evaporation rate. According to the purpose of this study, by reviewing the research literature and reviewing other research conducted in the field, a new approach to the study of parameters was achieved.

Description of the Structure and Anatomy of the Human Eye

The eye is the prominent organ of the first sense of the five senses, namely vision. The eyes are the most complex organ in the body after the brain. The eyes produce 36,000 bytes of information per hour, so about 85% of all your information is received through the eyes. A variety of light-sensitive organs are found in living organisms. The simplest types of eyes can only detect the presence of light around them, while more complex eyes are able to recognize shapes and colors, or some animals are sensitive to wavelengths longer than the visible wavelength of the human eye.

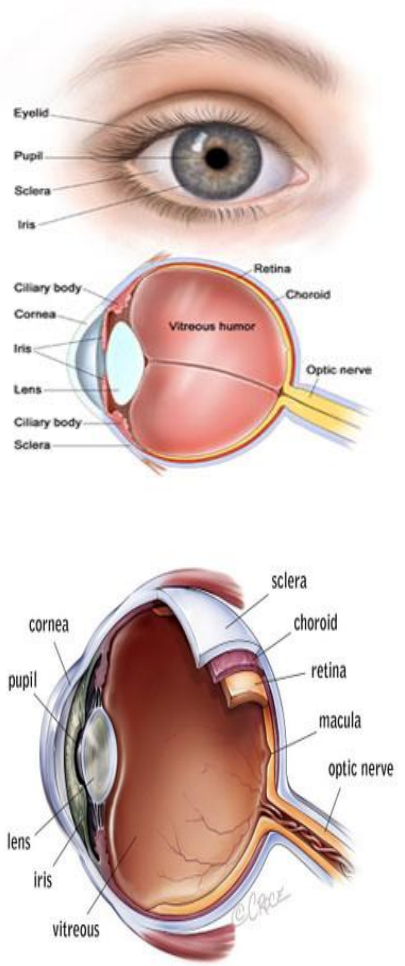

Figure 1. Components of the human eye

The human eye has components of the eyelid, eyelashes, conjunctiva, sclera, cornea, pupil, iris, vitreous, lens, aura, retina and choroid. The structure of the eye is like a sphere. In front of this sphere there is a transparent window called the cornea. Light enters the cornea from the outside environment and reaches the lens after passing through the pupil.

The lens focuses light precisely on the retina to create a clear image of the retina [16]. In order for objects to be seen accurately and clearly, it is necessary for the path that light travels through the eye to be clear and for the cornea and lens to focus light directly on the retina.

Research Background

A few examples of similar and related research by researchers in the field of biothermal transfer in the eye and other parts of the human body as well as the parameters affecting it are briefly described below. In 2007, Ghomashchi and Futurai studied the simulation of biothermal transfer in the human eye and Fluent software was used for modeling.

The results of modeling were compared with experimental results and effective parameters were investigated [3].

In 2013, Abdullah Zadeh studied heat transfer in the human eye, considering radiative heat transfer and displacement. In this study, the three-dimensional numerical solution of biogarm equations for turbulent flow in the human eye was investigated and the human eye was simulated in three dimensions and the temperature distribution was investigated [1].

In 2013, Firoozfar et al. Studied two-dimensional modeling of human hand heat transfer at ambient temperature of 30 °C by Fluent software and studied biothermal transfer in 4 organs including arm, forearm, palm and fingers [2].

In 1975, Broadwin and TOEFL modeled the phenomenon of heat transfer from the surface of the eye using the finite difference method. In this research, using a three-dimensional model consisting of two two-dimensional images, microwave radiation at different temperatures was studied and simulated, and maximum temperatures of 39.3 and 40.4 °C were obtained for the above radiation frequencies, respectively

[6]. In 1975, Guy et al. Modeled the effects of 2450 MHz on the rabbit's eye using the finite element method. Boundary conditions in this model included evaporation and transfer of radiant heat from the corneal surface and ocular tissue was considered homogeneous [5]. In 1981, Fieder et al. Showed in their research that the temperature of the corneal center is about 3.6 °C lower than body temperature, which was investigated using infrared imaging [4]. In 1982, Legendik performed a series of experimental measurements on rabbit eyes and used the results to determine the thermal properties of rabbit eyes using the finite difference method [14]. In 1988, Scott studied a two-dimensional finite element model of the human eye and studied the heat transfer equation in this model using the biothermal heat transfer equation and the temperature changes in the infrared state. In this model, 6 regions of ocular tissue are modeled and boundary conditions on the cornea and sclera are considered [15]. In 1989, Efron et al. Reported an average eye surface temperature of 34.3 °C using infrared imaging [17]. In a similar study,'s eye surface temperature was reported by Purslow et al. to be around 35 °C [8-9]. The main reason for this temperature difference is the effect of factors such as environmental conditions, age of test subjects and the like, all of which affect the temperature of the eye surface [7-18-19]. In 2006, Angie and O'Year proposed a two-dimensional model of the human eye to study the thermal characteristics under steady-state conditions using the element method. The results of this simulation have a much better agreement with the results of experimental measurements [10]. Angie and Ovi also studied the rotation of the aqueous humor in the anterior cavity of the eye and its effect on eye temperature changes using a two-dimensional model of the human eye. The results showed that the natural rotation of the aqueous humor increases the temperature and the temperature profile in the anterior cavity and cornea changes. They added an artificial heat source to the eye. The results of the model presented by them were not consistent with the experimental results and the model was limited. [10]. In 2008, Hein Oee et al. Presented a symmetrical three-dimensional radial model of the human eye. Their ocular borderline model studied temperature changes in the cornea during laser therapy. Energy uptake in the cornea was simulated and analyzed using Beer-Lambert law [11].

Introduction of Governing Equations in Biothermal Transfer

In 1948, Pence measured the temperature of the normal tissues of the human body and the blood vessels in the arm to adapt the theory of heat flow in the arm to the local rate of heat production in the tissue and the volume of blood flow.[12-15]. He proposed the first model that described the energy balance model in relation to blood perfusion and tissue metabolism. The bio-thermal equation of the pliers is a simplified form of the plier's formula, which is as follows:

$$\rho_t c_t \frac{\partial T_t}{\partial t_t} = \nabla . k_t \nabla T + \omega \rho_b c_b (T_A - T_V) + Q_{met} + Q''' \quad (1)$$

The left side of Equation (1) shows the thermal accumulation of tissue. The first expression to the right of Equation (1) indicates the transfer heat transfer and the second expression indicates the increase in blood perfusion due to blood flow through the tissue [16]. The third expression, Q met, is the heat generated by metabolism, and the last expression indicates the external heat source. The lowercase letters t and b represent the words tissue and blood, respectively [17].

The letters A and V represent arterial and venous blood, respectively. Density and c are heat capacity. T represents temperature, t represents time, k represents thermal conductivity and perfusion rate. There are generally three sources of energy:

q_b :Perfusion

Q_{met} :Heat due to metabolism

Q''' :External heat source

The eye is a living organ and, like other parts of the body, energy is transmitted to this organ through the bloodstream. But due to the visual function of this organ, the arteries of the eye are only in the choroidal area [18]. In addition, it is assumed that the heat generated by metabolism in this tissue is negligible, and in this case the only source of heat will be the transfer heat transfer through the bloodstream under normal conditions. In addition to the heat from the bloodstream, there is an external heat source [19].

Theory and Method of Numerical Solution

Material properties and thermal properties of each area of the eye using information from a similar study related to Ng [10]. Extracted and used, the information is presented in Table (1). On the other hand, in the present study, several areas of ocular tissue are homogeneous and isotropic [20]. The Pennes bioheat transfer equation has been used as the governing equation to express heat transfer in the eye in this study as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla(k\nabla T_t) + \omega\rho_b c_b (T_{a,in} - T_{v,out}) + Q \quad (2)$$

The two-dimensional model we have considered for the eye is based on the Ng and Ooi models [10]. You can see this model in figure (2):

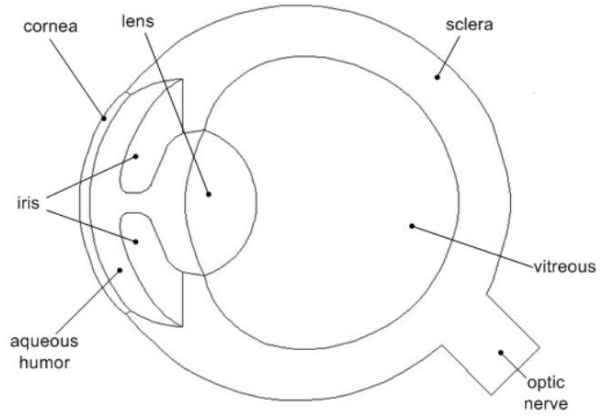

Figure 2. Two-dimensional model of the eye

Due to the same thermal properties in some of our areas, we consider corneal and aqueous, iris and sclera, lens, and vitreous as 4 separate areas [21-23]. The reason for this is related to the heat transfer equation, since heat transfer is our problem. The heat transfer is stable, so the part related to ∂T / ∂t is ignored. As a result, the terms ρ, c_p is not involved in the problem and the total thermal properties of an area can be reduced to k. And because of this we have divided the whole eye into areas in terms of thermal properties [24]. Figure 3 shows these four areas:

Table 1. Material properties of ocular tissues [10].

Density (Kg/m³)	Specific Heat (J / KgK))	Thermal Conductivity (W/mK)	Texture
1050	4178	0/58	**Cornea**
996	3997	0/58	**Clear**
1100	3180	1/0042	**Iris**
1050	3000	0/40	**Lentils**
1000	4178	0/603	**Vitreous**

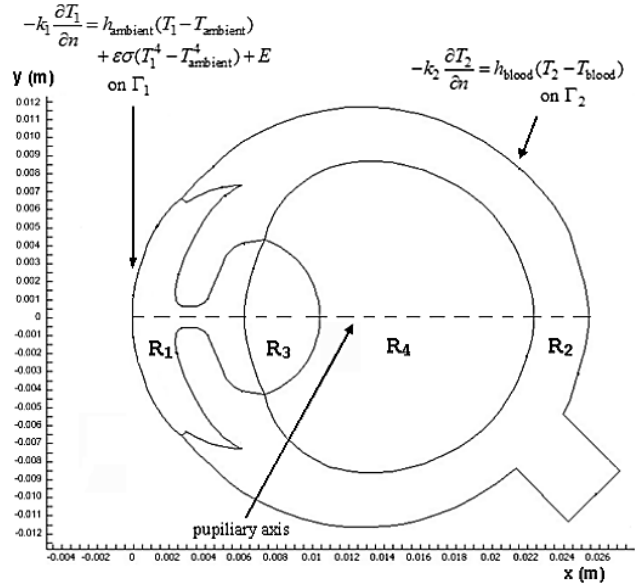

Figure 3. Division of the eye in terms of thermal properties

In this problem we have considered the temperature distribution in the steady state that we have:

$$\frac{\partial T}{\partial t} = 0 \qquad (3)$$

And the heat transfer equation is as follows:

$$\nabla(k\nabla T_t) + \omega\rho_b c_b(T_{a,in-}T_{v,out)+Q} \qquad (4)$$

That we have not given up ω.

Now we will examine the border conditions of different parts of the eye: The cornea is the only part of the eye that has direct contact with the outside environment and at the surface of the cornea there are three types of boundary conditions that we have considered in our modeling all three boundary conditions: Transfer heat transfer to the outside environment, the relationship of which is as follows: That we have not given up ω.

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$$-k_1\frac{\partial T_1}{\partial n} = h_{ambient}(T1 - Tambient) \qquad (5)$$

Where n is perpendicular to the cornea. 2- Transfer of radiant heat to the surface of the cornea with the outside environment:

$$-k_1\frac{\partial T_1}{\partial n} = \varepsilon\sigma(T_1^4 - T_{ambient}^4) \qquad (6)$$

Where K1 is the thermal conductivity of region 1, ie the cornea, and ε is the corneal diffusion coefficient and σ is the constant of Stephan Boltzmann, which are assumed to be constant. Corneal surface evaporation rate:

$$-k_1\frac{\partial T_1}{\partial n} = E \qquad (7)$$

Also, the inner surface of the eye, ie the environment of region 2, has a boundary condition of heat transfer with blood, which is related as follows:

$$-k_2\frac{\partial T_2}{\partial n} = h_{blood}(T2 - Tblood) \qquad (8)$$

K2 is the thermal conductivity of the second region, the sclera, and hblood is the heat transfer coefficient of blood circulation. The values of the parameters introduced in the above equations are shown in table (2).

Modeling in COMSOL Multiphysics Software 4.4

Today, process modeling and simulation are widely used in various fields of engineering, most of which are partial differential equations (PDE) expressing the mathematical nature of the process under study. Due to the existence of complex geometries as well as the simultaneous occurrence of various phenomena (momentum transfer, heat and mass transfer, chemical reactions, etc.)

Table 2. The number of parameters in the heat transfer equation

Control parameter	***Value***
Blood temperature $T_{blood\ (^{\circ}C)}$	**37**
Ambient temperature $T_{ambient}$($^{\circ}$C)	***25***
Emissivity of cornea ε	***0.975***
Blood convection coefficient h_{blood} ($Wm^{-2}(^{0}C)^{-1}$)	***65***
Ambient Convection Coefficient h_{blood}($Wm^{-2}(^{0}C)^{-1}$)	***10***
Heat flux loss due to tear evaporation E (Wm^{-2})	***40***
Stefan-Boltzmann constant σ ($Wm^{-2}(^{0}C)^{-1}$)	***5.67 x 10^{-5}***

It is impossible to solve the obtained equations by analytical methods and as a result numerical method are used. One of the numerical methods that is used successfully in various fields of engineering is the Finite Element Method (FEM). COMSOL Multiphysics software as a powerful modeling software uses this method to solve differential equations that the application of this software is expanding day by day in various industries. On the other hand, according to the solution of fluid flow equations in this software, this software is also included in the software of Computational Fluid Dynamics (CFD) software. As mentioned before, the two-dimensional eye model is formed by point-to-point method in the present study, so that to draw this model, more than 1000 separate points have been used for drawing in COMSOL software, which has high accuracy in drawing. To solve this problem, a two-dimensional, stable and biothermal transfer model has been used in COMSOL software, the detailed solution method is given in the appendix.

Discussion and Conclusion

After solving in COMSOL software, the results obtained are as follows, which we will analyze these results as follows: 5-1- Solve the problem by considering the values of the default parameters the solution with the default values of the desired parameters is presented in tables 1 and 2. In Figure 4, you can see the eye temperature contour. As expected, the more we move inside the eye (along the hypothetical axis), the higher the temperature, and we have the minimum temperature at the eye level with a temperature of 34.2 °C, and the maximum eye temperature. We have a temperature of 36.8 °C in the sclera [25].

These results are obtained with the same values as in section 2, and in subsequent sections we have a comparison of the results with the change of important parameters on the agenda.

In Figure 5 we have a temperature diagram relative to the external environment of the cornea, which is one of the important outputs in solving this problem. As you can see in this diagram, the temperature in the center of the cornea has its lowest value, 34.2 °C, which is the lowest temperature in the entire ocular tissue, and the two ends of the cornea have the highest temperature at the level of the cornea.

Figure 6 also shows the eye temperature diagram along the hypothetical axis drawn from the beginning of the cornea to the end of the sclera. As shown in this figure, the temperature in the center of the cornea has its lowest value and the temperature at the end.

The sclera has its highest value and this diagram is obvious because in the sclera we have the input flux due to heat transfer of blood flow with this side and in the cornea, we have 3 output fluxes which proves the accuracy of this diagram.

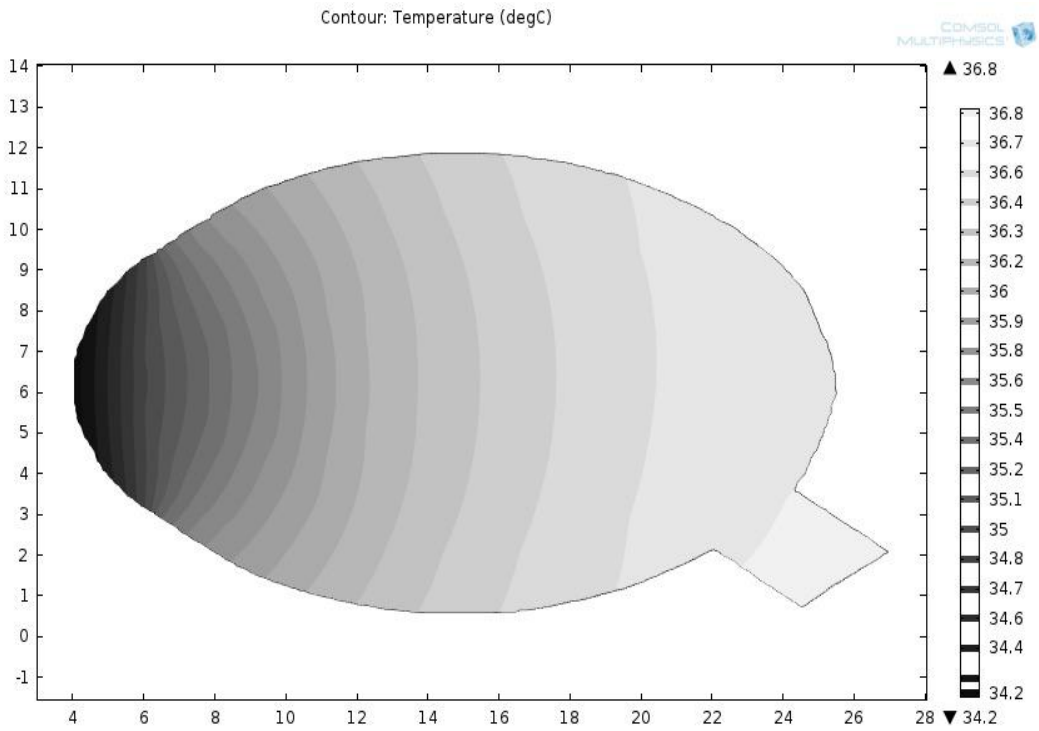

Figure 4. Eye temperature contour

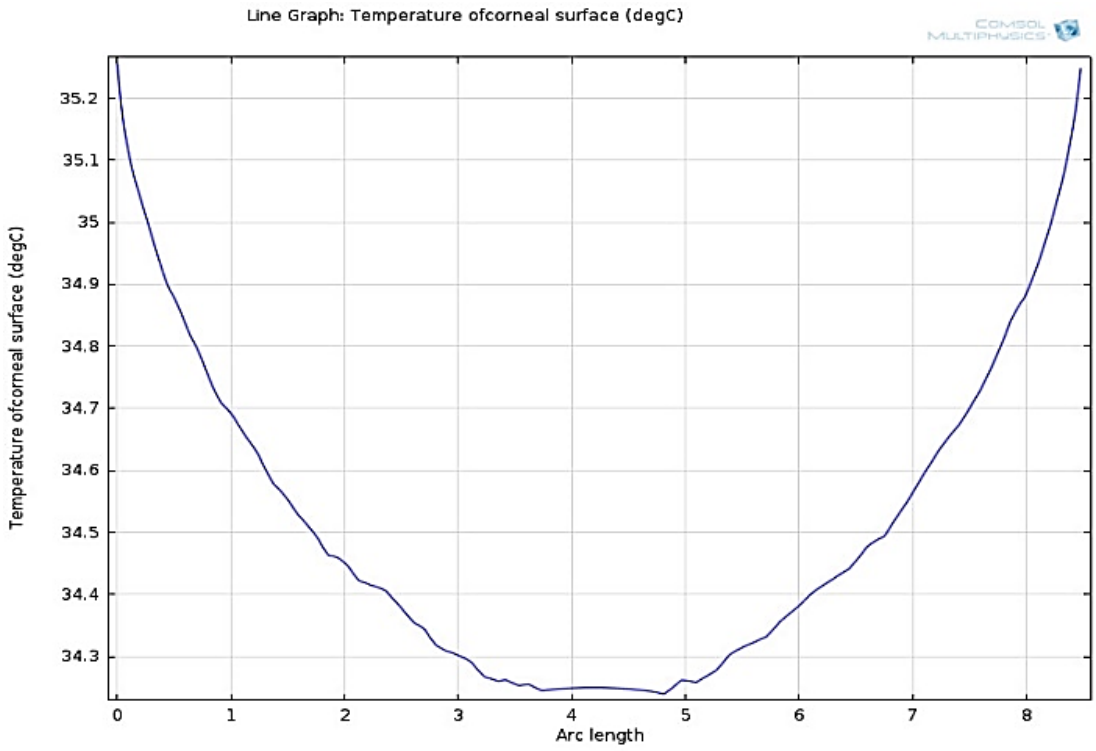

Figure 5. Diagram of corneal surface temperature relative to the external environment of the cornea

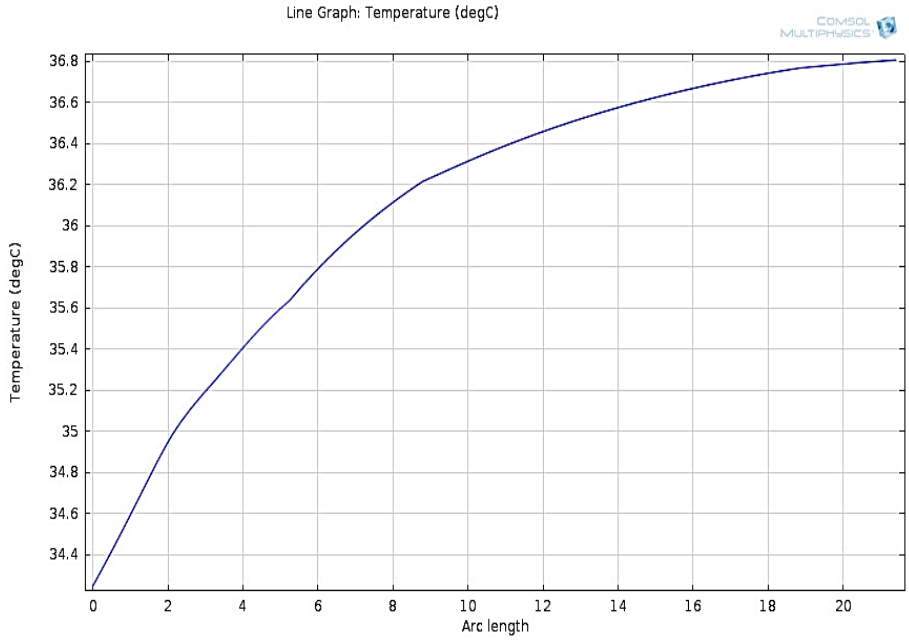

Figure 6. Diagram of eye temperature along the hypothetical axis

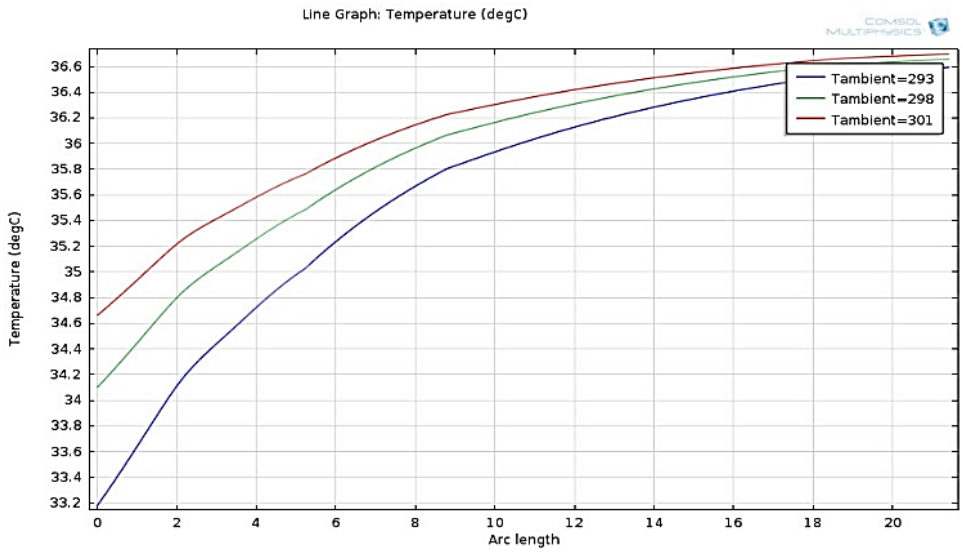

Figure 7. Comparison of eye temperature under different values of ambient temperature

Investigating the Effect of Ambient Temperature

Due to the difference in normal ambient temperature in different parts of the earth, we have studied different temperatures on the temperature of different areas of the eye. To do this, we have used three temperatures of 20, 25, 30 °C that diagram the eye temperature along the hypothetical axis (Figure 7). As can be seen from the figure 7, in general, the temperature of the eye increases with increasing ambient temperature, which is due to the reduction of heat loss at the surface of the cornea, the effect of which is less and less as we move along the hypothetical axis. The corneal center temperature is about 33.18 °C ambient temperature of 20 °C, about 34.2 °C ambient temperature of 25 °C and about 34.6 °C ambient temperature of 30 °C.

Investigating the Effect of Blood Temperature

In this section, we have studied the effect of different blood temperatures on eye temperature.

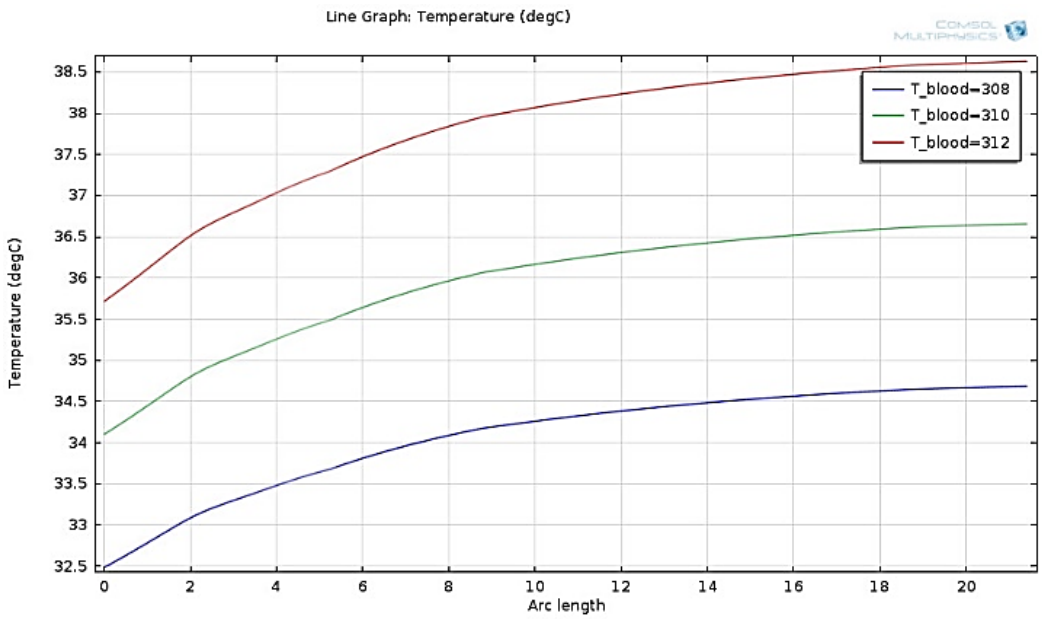

Figure 8. Diagram of eye temperature along the hypothetical axis of the eye by considering different values of blood temperature

We know that the normal blood temperature is 37 degrees Celsius, and for this part, we used three temperatures of 39, 37, 35 degrees Celsius, along with an eye temperature chart. You can see the hypothetical axis in Figure 8. As you can see from Figure 7, as the blood temperature rises, the overall temperature of the eye increases, which is obvious because the only heat flux entering the eye is the transfer of heat from the inlet to the sclera. The surface temperature of the eye will drop to 35.5 °C at 35 °C, to 34.2 °C at 37 °C and to 35.7 °C at 39 °C.

Investigating the Effect of Lens Conductivity

Now we will examine the effect of the thermal conductivity of the lens on the eye temperature, for which we consider 4 different thermal conductivity coefficients for the lens of the eye. We know that the normal value of the thermal conductivity of the lens is 0.4. We see the values of 0.2, 0.4, 0.5, 0.6 for the thermal conductivity of the lens in Figure 9.

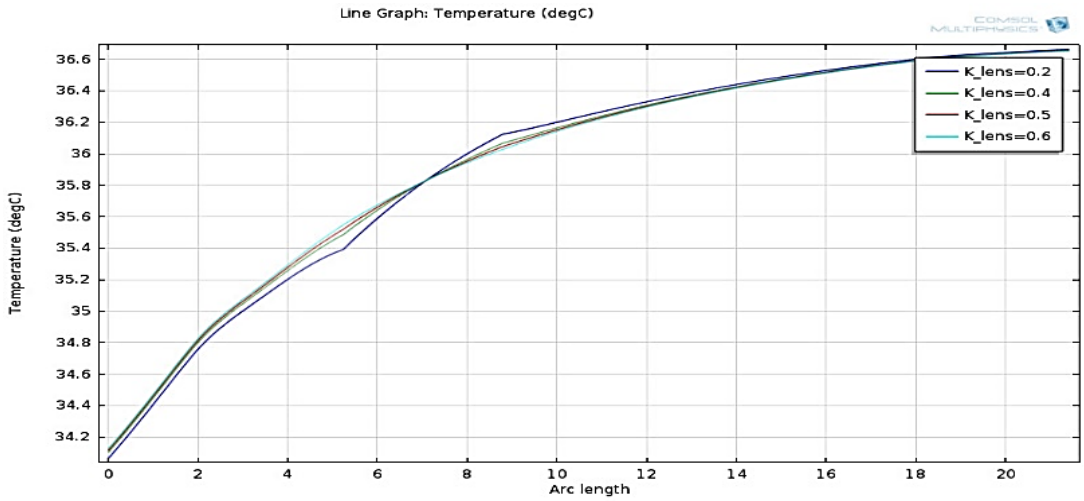

Figure 9. Eye temperature along the hypothetical axis with different values of eye thermal conductivity

As you can see in Figure 9, the higher the thermal conductivity of the lens on the surface of the cornea, the higher the temperature of the corneal surface, which results in better heat transfer to the sclera, but this effect is reversed in the sclera. The higher the thermal conductivity of the lens, the lower the temperature of the sclera, which is due to the increased heat transfer from the sclera to the cornea. In general, this effect is very small.

Investigating the Effect of Blood Heat Transfer Coefficient

We know that the normal rate of blood transfer coefficient is 65. In this section, we want to see the effect of this parameter on the temperature of different areas of the eye. For this, we examine the problem with blood transfer heat transfer coefficients of 115,100, 65 (Figure 10). As we can see in Figure 10, as the heat transfer coefficient of blood circulation increases, the temperature of different areas of the eye increases because the only input flux to the eye is due to the same heat transfer movement with blood.

Investigating the Effect of Corneal Surface Diffusion Coefficient

In this section, we have studied the effect of corneal surface diffusion coefficient, which is one of the radiative properties, and we have examined the corneal surface temperature with different values of this coefficient, which you can see in Figure 11. As is clear from the figure, the temperature of the corneal surface is inversely related to the amount of surface diffusion coefficient. The higher the diffusion coefficient, the lower the temperature in the cornea, and the lower the diffusion coefficient, the higher the temperature in the cornea. This study can also show the effect of eye color on corneal temperature. Colors with different diffusion coefficients have different effects. They are placed on the temperature of the corneal surface.

Investigating the Effect of Tear Evaporation Rate

Finally, we deal with the effect of tear evaporation rate on eye temperature, which after solving the problem with different values of tear evaporation rate, we get the number 12

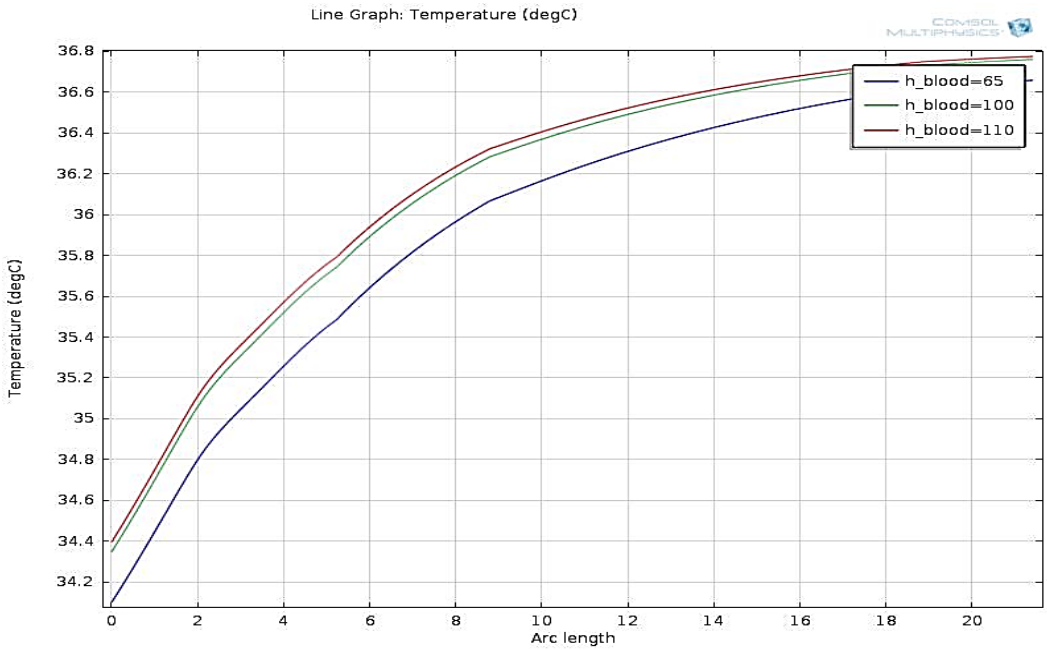

Figure 10. Eye temperature along the hypothetical axis for different values of the heat transfer coefficient of blood circulation

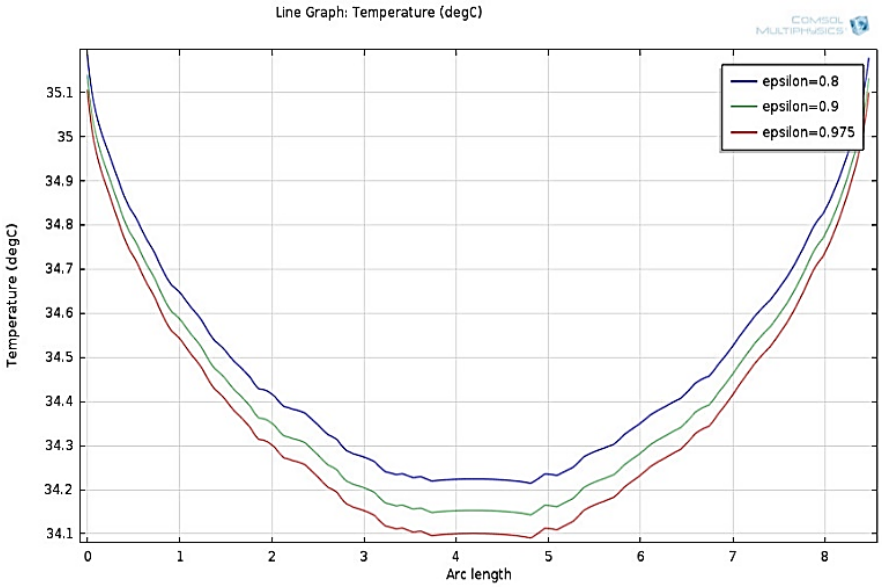

Figure 11. Corneal surface temperature for different values of emission coefficient

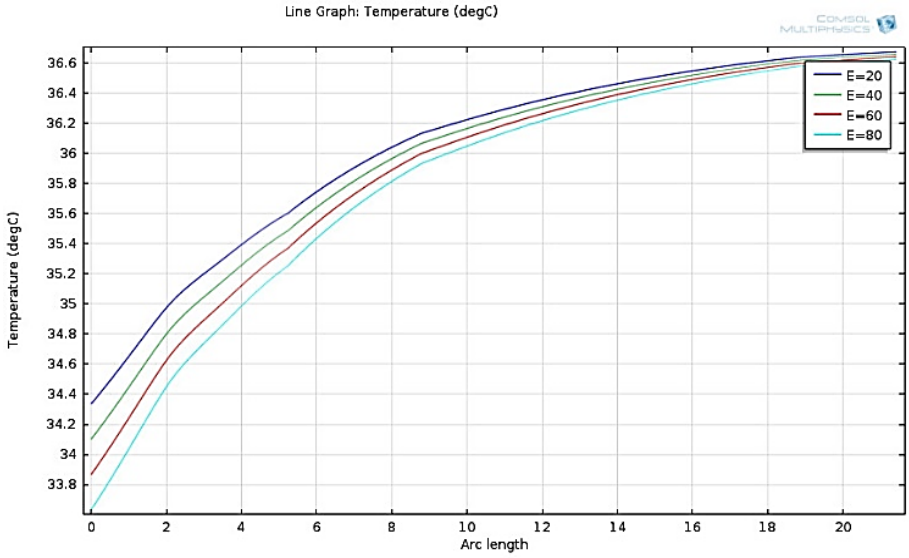

Figure 12. Eye temperature along the hypothetical axis for different values of tear evaporation rate

In Figure 12, we see that the greatest effect of the tear evaporation rate is on the surface of the cornea, which is inversely proportional to the temperature of the corneal surface, and the more we season the cornea along the hypothetical axis, the less this effect.

Conclusion

Examining the obtained results, it was found that the effect of blood temperature and ambient temperature on corneal surface temperature has the highest rate that different amounts of blood temperature have a significant effect on total eye temperature, but the effect of ambient temperature has moved along the hypothetical axis gradually reduced. Examining Figure 12, we find that the rate of tear evaporation does not have a significant effect on corneal surface temperature, and even if it were ignored, our results were acceptable with acceptable error. Also, by examining Figure 11, we found that radiation is an important factor in eye surface temperature, which, unlike the article [10], cannot be ignored and a significant error is made. A significant factor in ocular inflammation according to this study is high blood temperature, which can be caused by various medical factors, but finding this problem leads us to prevent and

treat this problem even without invasive eye measurement methods and only by measuring temperature.

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