Original Article

Temperature Distribution Simulation of the Human Eye Exposed to Laser Radiation

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Abstract:

Introduction: Human eye is a sensitive part of human body with no direct protection and due to its lack of protection against the external heat waves, studying the temperature distribution of heat waves on the human eye is of utmost importance. Various lasers are widely used in medical applications such as eye surgeries. The most significant issue in the eye surgeries with laser is estimation of temperature distribution and its increase in eye tissues due to the laser radiation intensity. Experimental and invasive methods to measure the eye temperature usually have high risks.

Methods: In this paper, human eye has been modeled through studying the temperature distribution of three different laser radiations, using the finite element method. We simulated human eye under 1064 nm Neodymium-Doped Yttrium Aluminium Garnet (Nd: YAG) laser, 193 nm argon fluoride (ArF) excimer laser, and 1340 nm Neodymium doped Yttrium Aluminum Perovskite (Nd: YAP) laser radiation.

Results: The results show that these radiations cause temperature rise in retina, lens and cornea region, which will in turn causes serious damages to the eye tissues.

Conclusion: This simulation can be a useful tool to study and predict the temperature distribution in laser radiation on the human eye and evaluate the risk involved in using laser to perform surgery.

Keywords: temperature; laser; radiation; eye.

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Introduction

Technology development in recent years has led to increase the use of telecommunication systems, wireless networks, lasers and other instruments all of which produce electromagnetic waves. Human eye is exposed to various types of waves all day long and due to lack of a protective layer (e.g. of skin) to absorb or reflect the electromagnetic waves, human eye has developed a high sensitivity to the dangers of such waves that transform to heat in the ocular tissues. A significant factor in regulating body temperature is blood circulation; therefore, a failure in proper blood circulation in most parts of the eye makes it vulnerable; even low temperatures can cause lens fogging, shrinkage, or damage to ocular tissues, particularly to cornea and the retina.

Most experimental methods that are performed to measure the temperature distribution are invasive in a way that they result in damage to eye tissues, and thus they are usually performed on animal's eyes. On human eye, we face a lack of empirical data, because measuring the temperature distribution in human eye is ethically and technically difficult. Most of these experiments have been limited to measuring only the surface temperature of cornea, and to date the temperature of other parts of the eye is ignored. Therefore, computational modelings are valuable tools for estimating the temperature and the potential damage that may be caused by thermal loads, as direct measurement is technically an impossible task *in vivo*[1].

In the past decade, research on the eye thermal characteristics led to advanced models of heat transfer of this organ. These models not only could be used to predict the external heat sources effects, but they could also be used to study and to treat certain eye diseases. Thermal models of eye provided a fairly precise temperature distribution of the inner parts of the eye based on the given conditions; they can therefore be used to determine and predict the location of tissue injury.

Nowadays, lasers are widely used in industrial and medical applications. As a matter of fact, use of laser systems with wavelengths covering electromagnetic spectrum from ultraviolet to visible and infrared can cause unintended adverse effects on human body, and especially to eye. However, with the advancements of technology, various types of lasers are now used in many eye surgeries. This is the reason why its harmful effects on eye tissues need to be studies to prevent the possible damages to this organ[2]. Prediction and calculation of these effects, most of which are thermal, help ophthalmologists to select the type of laser and to adjust its parameters for these operations, to have minimum damage or side effects[3,4,5].

Light interaction with eye tissue has four different ways: transmission, reflection, scattering, and absorption. In this case, absorption is, to a high extent of probability, the most important process in modeling this interaction, since absorbed photon energy by tissue could be converted into heat.

In order to derive a model that describes the thermal effects of laser on eye, the heat transfer in eye needs to be calculated. In biological tissues this is achieved by using bio-heat transfer equation, which takes into calculation the different types of heat transfer[5,6] scenarios.

There are many models that express the heat distribution in the human eye. Most of these models calculate the heat distribution in the eye, using the finite element method (FEM). Scott et al. considered 2-D FEM model to simulate the human eye heat transfer due to electromagnetic waves radiation[7,8]. Shafahi et al. investigated the temperature distribution in different parts of eye using different models[1]. Heydari et al. has solved the steady-state heat analysis of human eye using the three-dimensional finite element method[9]. Amara et al. acquired temperature distribution model of human eye under pulsed Nd:YAG laser radiation and Chua et al. and Cvetkovic et al. investigated temperature distribution in the human eye, using the FEM for that kind of laser[3,4,6]. Narasimhan et al. has been studying the thermal effects of Nd: YAG laser in retinal surgery[5].

The model results obtained in this study have been used to provide heat distribution in human eye exposed to the Nd: YAG laser with a 1064 nm wavelength, ArF excimer laser with 193 nm, and Neodymium doped Yttrium Aluminum Perovskite (Nd:YAP) laser with 1340 nm wavelength.

Method

Anatomy of the human eye

Eye is a very complex optical system and also one of the most sensitive organs in human body. In order to understand the development of the model, a basic understanding of the eye anatomy is necessary. Eye comprises several parts: the anterior part of the eye which includes the cornea (the clear outer covering of the eye), the anterior chamber (filled with aqueous humor) and the iris; and the posterior part of the eye which includes the lens, the ciliary bodies (tissue that holds the lens to the sclera known as capsule), vitreous chamber (filled with vitreous humor), retina (light-sensitive back of the eye) and sclera (white part of the eye). Blood flow occurs only in the back of the eye, i.e., in the sclera and retina region[7]. You can see different parts of the human eye and their distances on pupillary axis in figure 1.

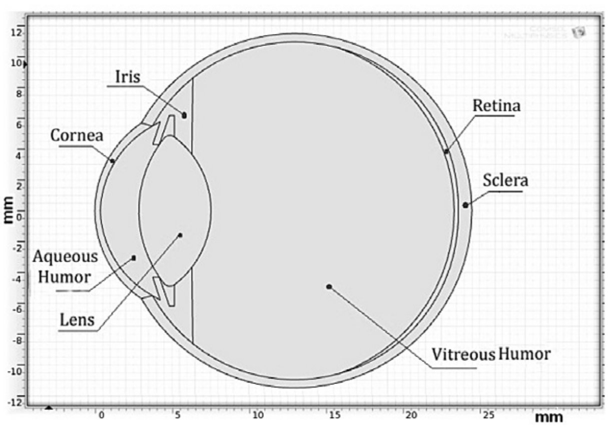

Figure 1. Different Parts and dimensions of human eye

Geometry and properties of the human eye

Figure 1 shows the cross section of the eye. Eye diameter is about 24 mm along the pupillary axis and 23 mm along the vertical axis[11]. The posterior half of the eye is usually considered as spherical. All parts of eye are assumed to be homogeneous and symmetric around the pupillary axis.

In this model, the authors assumed that the laser light runs into the pupillary axis, thus, in this respect all parts of the eye are affected by laser light. Thermal properties of various components in human eye are listed in Table 1.

Mathematical model of heat transfer in human eye

The mathematical model of human eye is based on Penne's bio-heat transfer equation; this equation is identified as the calculation reference for heat effects in biological tissues[12]. In Penne's model, the rate of temperature increase in the tissues is obtained by sum of heat conduction into the tissue, metabolic heat generation, and heating (cooling) effects due to blood circulation in the tissue:

$$\rho_t c_t \frac{\partial T}{\partial t} = \nabla(k\nabla T) + w_b \rho_b c_b (T_a - T) + Q \quad (1)$$

Where ρ_t and ρ_b are, respectively, the tissue and blood density (kg/m^3), c_t and c_b are, respectively, the specific heat of tissue and blood (J/kg.K): k is the thermal conductivity (W/mK), T is temperature (K), t is the time (s), w_b is blood flow rate (m^3/s), T_a is the ambient temperature (K), and Q is the heat generation (W/m^3). Heat generation varies due to metabolism or external sources such as radiation of electromagnetic waves or laser.

Table 1. Thermal properties of various parts of human eye 5, 6

Eye tissue	Property		
	Thermal conductivity K(Wm^{-1}K^{-1})	Specific heat capacity C (JKg^{-1}K^{-1})	Density ρ(kgm^{-3})
Cornea	0.580	4178	1050
Aqueous humor	0.578	3997	1050
Lens	0.400	3000	1000
Iris	1.680	3650	1100
Vitreous humor	0.594	3997	1000
Retina	0.565	3680	1000
Sclera	0.580	4178	1000
Blood	0.530	3600	1050

The first two terms on the right of the bio-heat equation (1) account for heat transfer due to thermal conduction and blood perfusion through the eye. Because only a small part of the entire eye is perfused and includes metabolic activity, these two terms can be neglected, resulting in the final governing equation:

$$\rho_t c_t \frac{\partial T}{\partial t} = k\nabla^2 T + Q \quad (2)$$

For steady state solution and with no external heat source, equation (2) reduces down to:

$$k\nabla^2 T = 0 \quad (3)$$

Boundary conditions can be defined for the system as follows[7,13]:

A) In the back of the eye, heat is transferred from blood in the ophthalmic artery to the sclera:

$$k\frac{\partial T}{\partial n} = h_{bl}(T - T_{bl}) \quad (4)$$

In equation (4), n is the normal direction to the surface boundary, h_{amb} is the heat transfer coefficient between blood and eye (65 W/m^2.K) and T_{amb} is blood temperature (37°C).

B) At cornea, heat loss from the eye occurs through convection, radiation, and tear evaporation:

$$k\frac{\partial T}{\partial n} = h_{amb}(T - T_{amb}) + \sigma\varepsilon(T^4 - T_{amb}^4) + E \quad (5)$$

Where h_{amb} represents the heat transfer coefficient between the eye and the ambient environment (14 W/m^2.K), T_{amb} is the ambient room temperature (30 °C), σ is the Stefan - Boltzmann constant (5.67 * 10^{-8} W/m^2 K^4), ε is the emissivity of the eye, and E is eye surface evaporation (40 W/m^2)[13].

C) Assuming the eye is symmetric around the pupillary axis (perpendicular to the cornea surface).

$$k\frac{\partial T}{\partial n} = 0 \quad (6)$$

Simulation of laser source

Energy density Q(r, z, t), absorbed by the eye tissues in cylindrical coordinates (r, z) is correspondent to equation (7)[5]:

$$Q(r,z,t) = \alpha I(r,z,t) \quad (7)$$

Where α is the wavelength dependent on the absorption coefficient of the specific tissue. In biological tissues, absorption is mainly due to presence of water molecules, proteins, pigments, and other macromolecules. The absorption coefficient strongly depends on the wavelength of incident laser radiation. Figure 2 indicates the changes of absorption coefficient in cornea, and retina tissues depend on various wavelengths of electromagnetic radiation[6]:

Various eye tissues absorption coefficient for Nd: YAG laser, ArF excimer laser and Nd:YAP laser have been shown in Table 2:

In equation (7), I is the laser intensity which is attained by the following equation[5]:

$$I(r,z,t) = I_0 \exp(-\frac{2r^2}{w^2} - \alpha z)\exp(-\frac{8t^2}{\tau^2}) \quad (8)$$

Where I_0 is the incident value of intensity; w is the beam waist, and τ is the laser pulse duration. For a given laser parameter, the laser intensity at the cornea is calculated from[6]:

$$I_c = \frac{4P}{d_c^2 \pi} \quad (9)$$

Where P is the laser power and d_c is the beam diameter on the cornea. Taking into account the focusing action of the lens, diameter of the image and intensity on the retina is calculated from[6]:

$$d_r = 2.4\ \frac{\lambda f}{d_p} \quad (10)$$

and

$$I_r = I_c \frac{d_p^2}{d_r^2} \quad (11)$$

Where λ is the laser wavelength, f is the focal distance of the lens, and d_p is the diameter of pupil opening. From these values, we now can calculate the intermediate values for the intensity and energy density along the various eye tissues.

An example of this kind of lasers, in industrial application such as welding, has pulse energy in range of 1-20 J and 10 ms pulse width. A percentage of this laser is reflected and scattered from metal objects. After all, the parameters which have been considered for calculation due to these three types of laser were; 1.5 mJ pulse energy, 10 ms pulse duration, 0.5 mm the diameter of the radiated laser and the 3 mm diameter of the pupil opening.

Numerical methods

Analytical solution of the Penne's bio-heat transfer equation is limited to a few simple geometries with high degree of symmetry, but using the Finite Element Method we are able to solve problems on complex geometry, such as human eye. We use Solidworks® for

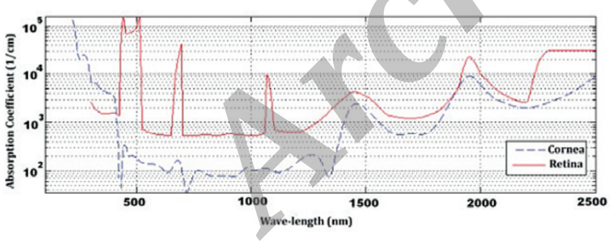

Figure 2. Absorption coefficient changes for cornea and retina to wave-length

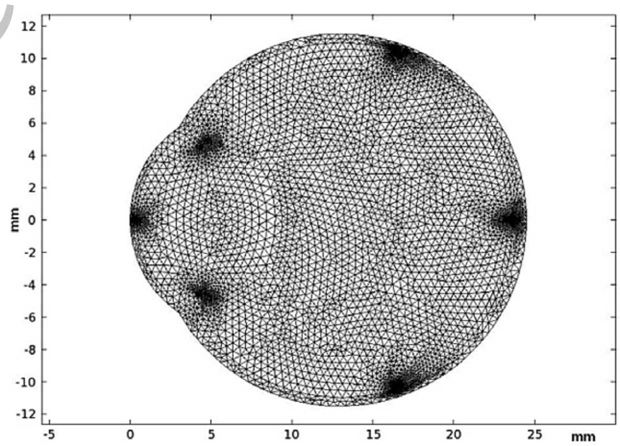

Figure 3. The human eye meshing using triangular elements

Table 2. Absorption coefficient of the various components of the human eye [6,10]

Eye Tissue type	Absorption coefficient(cm^{-1})		
	193 nm ArF excimer laser	1064 nm Nd:YAG laser	1340 nm Nd:YAP laser
Cornea	270000	113	240
Aqueous humor	2228	35	222
Lens	2558	43.5	235
Vitreous humor	542.7	20	224
Retina	6526	10000	1150
Sclera	28800	634.5	340

geometric modeling and Comsol® 4.2 to simulate and solve equations based on the finite element method. Eye meshing has been done in 21,853 Triangular elements which are shown in figure 3:

First, the equation is solved for the steady-state case, i.e., when no external heat sources are present, and latter, these results will be used as initial conditions in the time domain analysis equation with included external heat source, i.e. laser radiation.

Results

steady state

The results for the steady-state case temperature distribution in the human eye along the pupillary axis are shown in figure 4.

Also, the steady-state temperature distribution profile is shown in Figure (5).

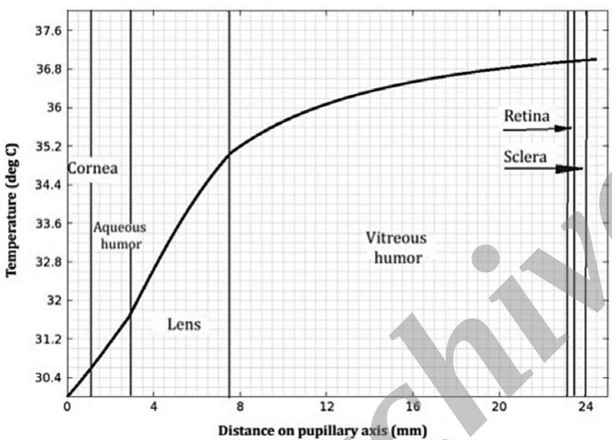

Figure 4. The steady-state temperature distribution on the pupillary axis

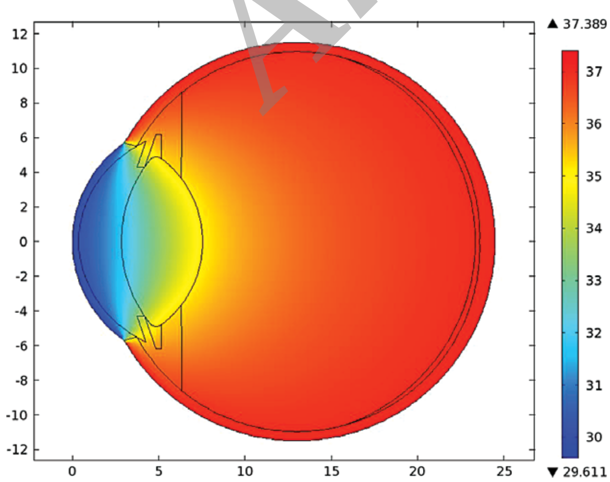

Figure 5. Steady-state temperature distribution in human eye

Steady-state case results, used latter as initial condition for time-domain analysis, are in a good agreement with a number of papers[1,3,4,6], and [7]. One can note on figure 4 the steady rise of temperature from anterior to posterior parts of the eye, with steepest slope being within lens tissue. The underlying reason for this is the lowest value for thermal conductivity of lens, compared to other eye tissues.

Time domain analysis (Transient)

Figures 6,7 and 8 illustrate the results of time-domain analysis temperature distribution along papillary axis. For Nd: YAG laser, maximum temperature after applying a 0.01 second pulse approaches to 94.8 °C. This temperature occurs in the retina due to high absorption of Nd: YAG laser on the retinal tissue (Figure 6).

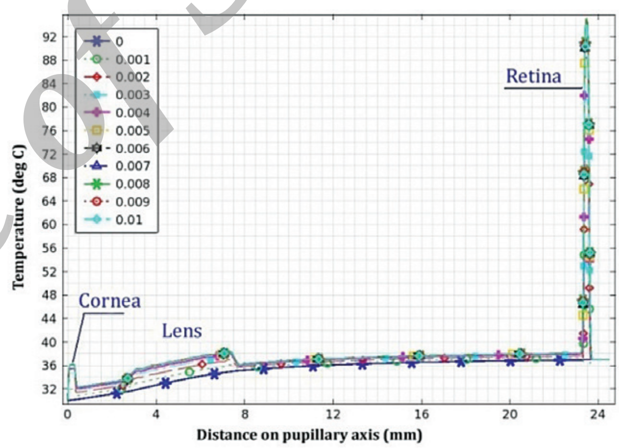

Figure 6. Time domain analysis temperature distribution on pupillary axis under Nd:YAG laser radiation

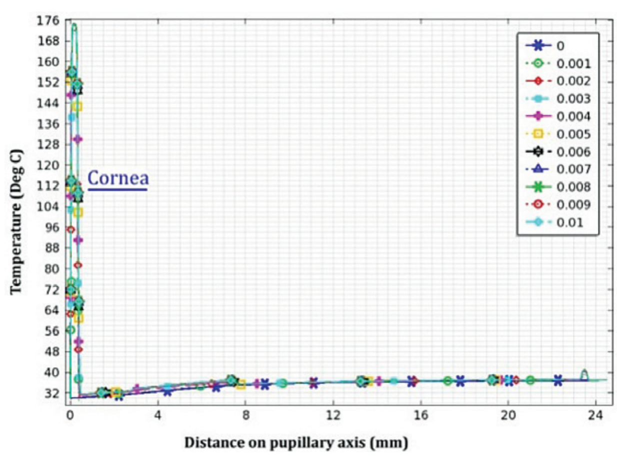

Figure 7. Time domain analysis temperature distribution on pupillary axis under ArFexcimer laser radiation

Figure 7 indicates time domain analysis temperature distribution under ArF excimer laser radiation. After 0.01 s radiation, as shown as figure 7, temperature in anterior part of the eye, especially cornea, rises to 175.19°C. This is important since excimer lasers are used in surgical operations that reshape the surface of cornea by process of photoablation.

Eventually, figure 8 illustrates the temperature distribution of human eye under 1340 nm Nd:YAP laser. It shows that under 0.01 s Nd:YAP radiation, lens temperature rises to 53.238 °C.

Also, figure 9 indicates the transient temperature distribution profile for Nd:Yag laser (a), ArF excimer laser (b) and Nd:YAP laser(c). The results obtained from simulation are consistent with the papers[5,6]. It can be inferred that, with the temperature achieved in eye tissues, this amount of laser radiation will cause serious injury and damage to human eye tissues[6] and [2].

Conclusion

Thermal simulation of the human eye, when exposed to laser beam, is obtained through using Penne's bio-heat equations. Accordingly, heat transfer equations can be solved in both steady-state and transient for this model. Likewise, the temperature distribution in human eye is achieved in these cases. The findings of this study indicate that for Nd:YAG laser with a 1064 nm wavelength, 1.5 mJ pulse energy and 10 ms pulse width, the maximum temperature in the retinal tissue is 94.8°C. Furthermore, under ArF excimer laser radiation and with 193 nm wave length and the other characteristics similar to past laser, the maximum temperature in the cornea is 175.2 °C and for Nd:YAP laser with 1340 nm wavelength, the maximum temperature in lens tissue is 53.2 °C. The summarized

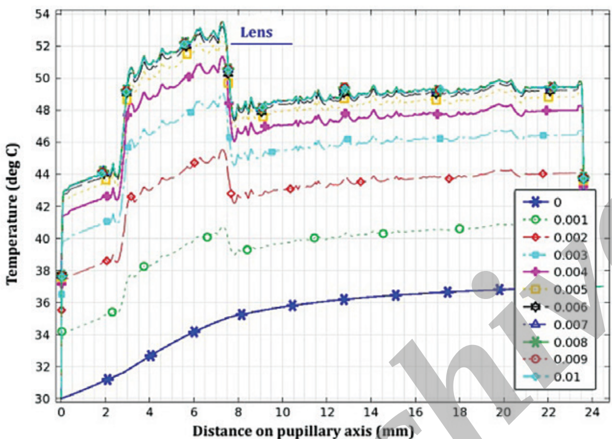

Figure 8. Time domain analysis temperature distribution on pupillary axis under Nd:YAP laser radiation

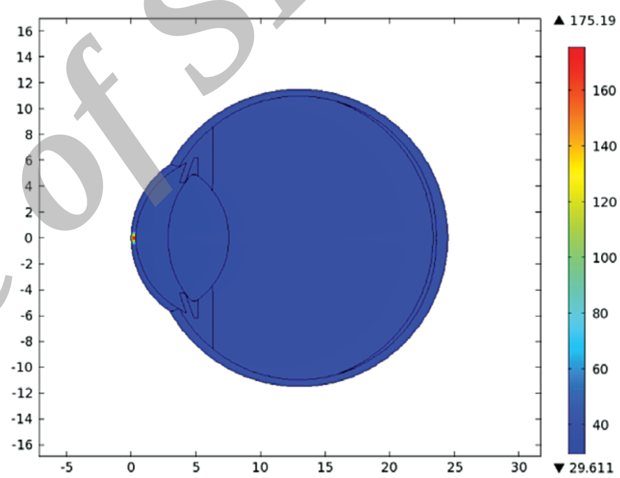

Figure 9b. Transient-state temperature distribution in human eye under ArFexcimer laser radiation

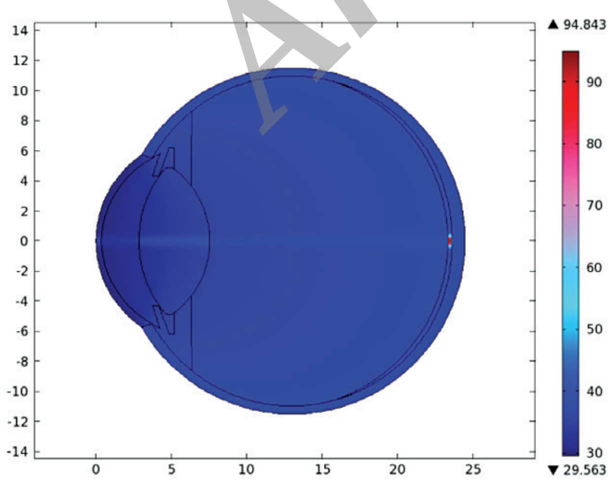

Figure 9a. Transient-state temperature distribution in human eye under Nd:YAG laser radiation

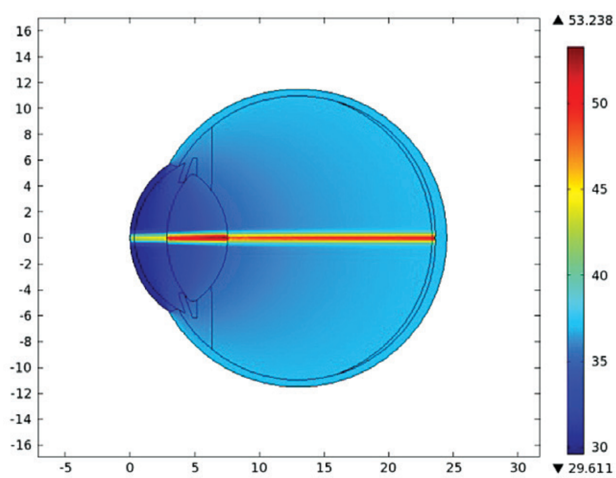

Figure 9c. Transient-state temperature distribution in human eye under Nd:YAP laser radiation

Table 3. Maximum temperature of eye tissues exposed of considered lasers

Laser type	Wave length (nm)	Max. Temperature (°C)	Effected tissue
Nd:YAG	1064	94.8	Retina
ArF Excimer	193	175.2	Cornea
Nd:YAP	1340	53.2	Lens

results are shown in Table 3.

The results suggest that eye tissues are highly sensitive and even vulnerable to these types of laser radiation.

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