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Evaluation of Thermal Responses of the Different Layers of Human Eye's Cornea

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Abstract
LASER is a form of electromagnetic radiation that converts light energy to heat energy. It is a widely used, non-invasive procedure for correcting refractive errors in ophthalmology. This study reports the evaluation of the thermal responses of human corneal layers when exposed to this thermal energy from LASER. The investigations took place in the simulation environment of COMSOL Multiphysics, where we modeled the eye cornea with its five different layers: epithelium, Bowman's layer, stroma, Descemet's membrane, and endothelium, from outermost to innermost. The LASER had the wavelengths of 193 nm, a pulse duration of 2 ns, and a heat flux of 1000 W/m². The total cornea thickness was 0.76 mm, and thermal conductivity was 0.35 W/m K. The stroma responded to heat values of 330 K as the highest, while the endothelium value was 285 K. This difference in values highlights that the thermal response of the tissue is influenced by certain elements, which are the thickness of the tissue, the thermal conductivity, and the heat capacity of the tissue. The finding of this study is very essential in facilitating the LASER refractive surgeries in the ophthalmology field.

Keywords: COMSOL, Human eye's cornea, LASER, Thermal conductivity, Thermal response.

Introduction

The human eye is an organ that reacts to light and allows vision; it can differentiate between about 10 million colors and is possibly capable of detecting a single photon (Profile, 2020) . The eyeball can be compared with an almost spherical shell housing a nucleus of transparent substances. The shell, in turn, is formed by three concentric membranes that are structurally and functionally different. The outer membrane is the fibrous coat, consisting of a larger and opaque posterior portion, the sclera, and a transparent, less extensive anterior portion, the cornea (Bertelli, 2019). The cornea is transparent tissue divided into five layers: epithelium, Bowman's layer, stroma, Descemet's membrane, and endothelium (Rates *et al.*, 2022). The corneal stroma accounts for about 90% of the corneal thickness (Vaughan & Asbury's, 2018).

Refractive error is a problem with focusing light accurately on the retina due to the shape of the eye (Saleh *et al.*, 2021). Refractive error happens when the optical system of the non-accommodating eye fails to bring parallel rays of light to focus on the retina (Maduka *et al.*,

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2021). Refractive error is an increasingly serious public health problem around the world (Liu *et al.*, 2022). The most common types of refractive error are myopia (shortsightedness), hyperopia (longsightedness), astigmatism (different types of refraction in the same eye), and presbyopia (reading defect). Presbyopia is an age-related condition, which branches from the gradual loss in the eye's capability to change its optical power; it manifests as an incapability to focus on objects, often leading to signs like visual discomfort, eye stress, and headache, after around 45 years of age (Karkhanis *et al.*, 2021).

Choices for correcting refractive errors include eyeglasses, contact lenses, or refractive surgery (Nour ., 2023).Corrective lenses are the most common method for correcting refractive errors, with options including spherical lenses, bifocal lenses, progressive lenses, and contact lenses. Refractive surgery involves reshaping the cornea using a LASER to overcome refractive errors and improve light focus on the retina. LASER means Light Amplification by Stimulated Emission of Radiation (Saraswathi *et al.*, 2022). Therefore, surgeons usually use the excimer laser ArF with radiation of 193 wavelengths (Razhev *et al.*, 2017). Consequently, the use of small-diameter laser beams provides very smooth corneal treatment (Abdelhalim and Hamdy, 2021). LASIK is proven to be a reliable, fast, and safe technique for corneal refractive surgery; literature reported its successful use for treating hyperopia. However, reports on its use for treating myopia are insufficient in the literature.

More than 27 million eyes had successfully been treated with LASIK refractive surgery all around the world (Pajic *et al.*, 2017). Today, the use of UV lasers for eye surgery has become an integral part of ophthalmic surgery (Razhev *et al.*, 2017). LASER has been extensively utilized in vision correction by the application of the corneal reshaping technique (Han *et al.*, 2020). LASIK surgery is normally performed in the stroma layer, which represents 90% of the cornea structures (Abdelhalim *et al.*, 2021). LASER refractive surgery is recognized as an extremely effective and safe procedure for low to moderate levels of refractive error (Ang *et al.*, 2021).

The focus of this study was evaluating the thermal responses of human corneal layers when exposed to thermal energy from LASER to facilitate researches on the use of LASER for treating myopia. The evaluation took place in the simulation environment of COMSOL Multiphysics. Finding from the results, we noticed that five different layers of the cornea had different thermal properties, and thus the absorption process in the cornea is gradual. This absorption showed that the cornea can be expanded due to thermal energy absorption from the laser. As such, problems associated with contraction or expansion by the cornea can be addressed through the use of LASER as the source of thermal energy.

Method

The human cornea was modeled in the COMSOL Multiphysics environment. The cornea radius of the curvature model is around 7.6 mm (Trembly, 2000). The total thickness of the human cornea is 0.68 mm (Shafahi and Vafai, 2010). The thermal conductivity of human cornea is 0.35 W/mK (Profile, 2020). The five layers of the cornea have been modeled. Each layer was exposed to an excimer laser of 193 nm wavelengths at a pulse duration of 2 ns with a boundary heat source of 1000 W/m².

The thermal responses of the different layers of cornea have been solved by the heat diffusion equation by COMSOL Multiphysics simulation.

$$\rho c_\rho \frac{\partial T}{\partial t} + \nabla.(-k \nabla T) = Q + Q\ ted$$

Where ρ is the density of the tissue, c is the specific heat capacity of the tissue, T is the temperature of the tissue, t is time exposed by laser, Q is the heat generated by unit volume by the laser energy, Q ted is heat generated due to mechanical effects and k is the thermal conductivity of the tissue

Results and Discussion

Evaluating the thermal responses of different corneal layers using COMSOL multiphysics involves simulating heat transfer and biological responses under specific conditions. The study types are transient and time-dependent, considering the plus duration of 2 ns and the specific heat capacity of each corneal layer. The boundary heat source of this study was 1000 W/m^2.

Table 1: Results of thermal responses of cornea layers and overall cornea exposed to 193 nm of excimer laser at 2 ns.

Cornea layer's	T (k)	C(J/kgK)	K(W/mK) Time(ns)	t(mm)	λ(nm)		**t(mm)**	**λ(nm)**	**Time(ns)**	**Cornea layer's**
Epithelium	300	3300	0.8	0.05	193	2	0.05	193	2	Epithelium
Bowman's layer	295	3250	0.4	0.012	193	2	0.012	193	2	Bowman's layer
Stroma	330	3600	0.18	0.5	193	2	0.5	193	2	Stroma
Descemet's membrane	290	3200	0.3	0.01	193	2	0.01	193	2	Descemet's membrane
Endothelium	285	3150	0.2	0.005	193	2	0.005	193	2	Endothelium
Cornea	340	3642.5	0.35	0.68	193	2	0.68	193	2	Cornea

Epithelium layer response

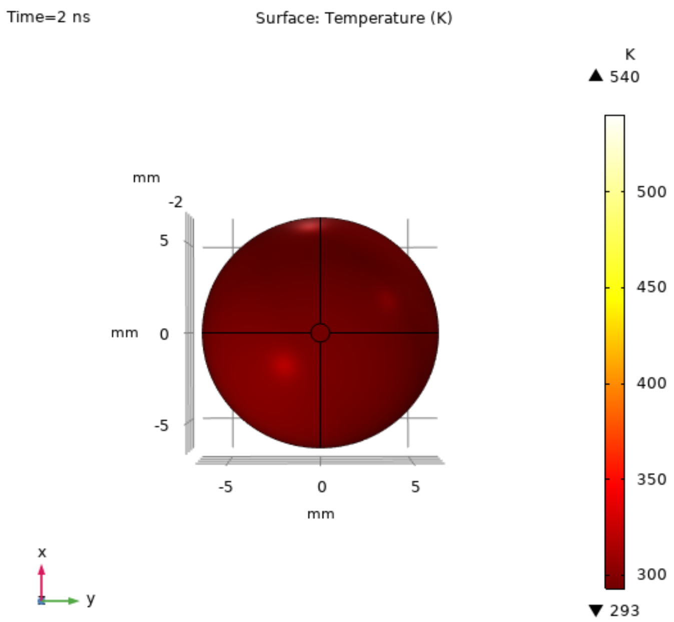

Figure 1: Thermal response of epithelium layer exposed to 193nm of excimer laser at 2 ns.

The epithelium is the outermost layer, the thermal response of the epithelium is 300 K, as seen in Table 1 and indicated by its brown Colour in Figure 1. The epithelium, when exposed to 193 nm of excimer laser for 2 ns, revealed a thermal response of 300 K due to its thickness of 0.5 mm, thermal conductivity of 0.8 W/mK, and heat capacity of 3300 J/kg K.

Bowman's layer response

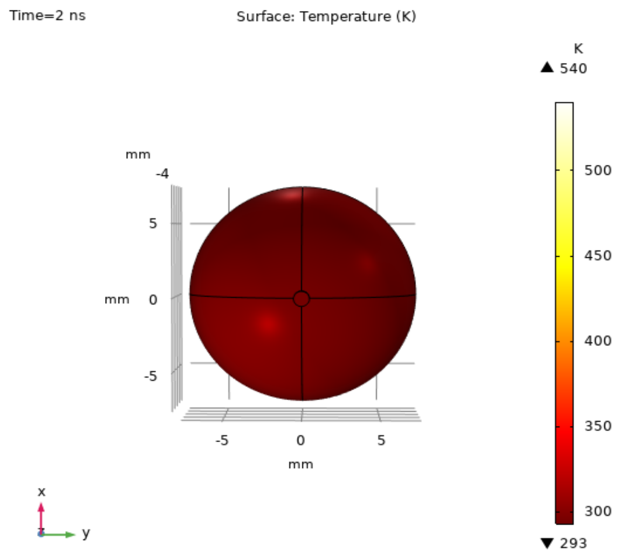

Figure 2: Thermal response of Bowman's layer exposed to 193nm of excimer laser at 2 ns.

Bowman's layer is the second layer of the cornea, its thermal response is 295 K, as seen in table 1 and indicated by its brown Colour in figure 2. Bowman's layer, when exposed to 193 nm of excimer laser for 2 ns, exhibited a slightly lower thermal response of 295 K. This reduction is due to its thickness of 0.012 mm, thermal conductivity of 0.3 W/mK, and heat capacity of 3250 J/kg K.

Stroma layer response

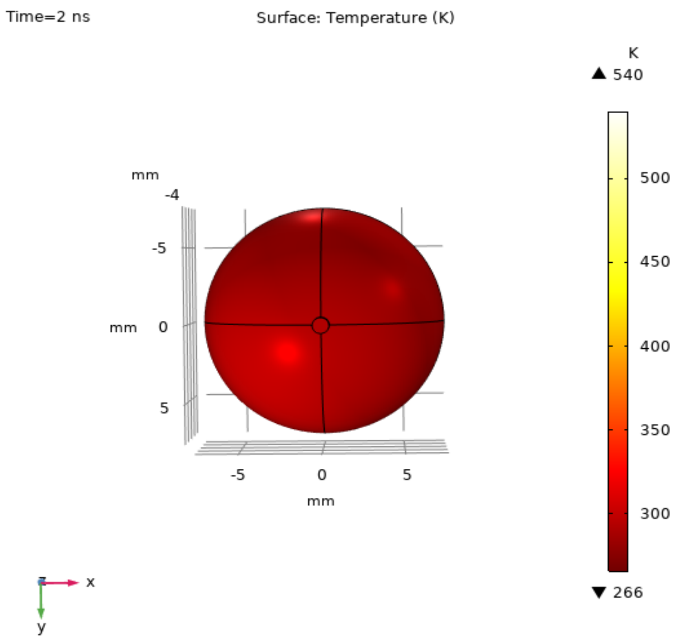

Figure3: Thermal response of stroma layer exposed to 193nm of excimer laser at 2 ns.

Stroma layer is the middle of the cornea; its thermal response is 330K, as seen in Table1 and indicated by its brown-red Colour in Figure 3. The stroma, when exposed to 193 nm of excimer laser for 2 ns, noted the highest thermal response of 330 K. This increase is due to its thickness of 0.5 mm, thermal conductivity of 0.18, and heat capacity of 3600 J/kg K. Because the stroma is the thickest layer of the cornea.

Descemet's membrane response

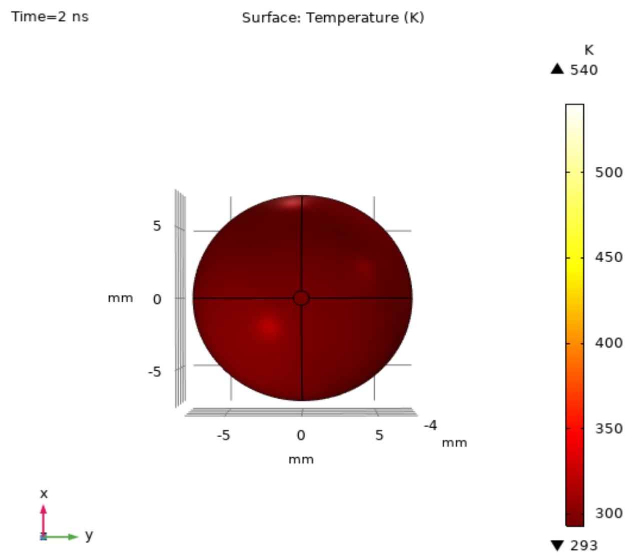

Figure 4: Thermal response of Descemet's membrane exposed to 193nm of excimer laser at 2 ns.

Descemet's membrane in the back of the stroma, its thermal response is 290 K, as seen in Table1and indicated by its brown Colour in Figure 4. Descemet's membrane, when exposed to 193 nm of excimer laser for 2 ns, showed a lower thermal response of 290 K, due to its thickness of 0.01 mm, thermal conductivity of 0.3 W/mK, and heat capacity of 3200 J/kg K.

Endothelium layer response

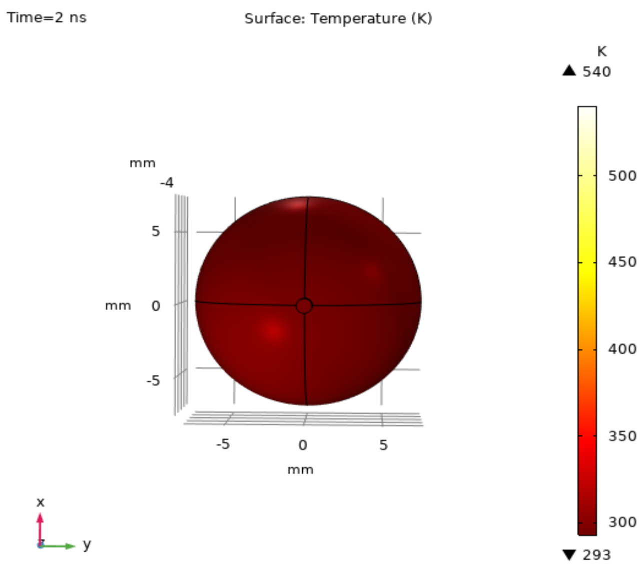

Figure 5: Thermal response of endothelium layer exposed to 193 nm of excimer laser at 2 ns.

Endothelium is the innermost layer of the cornea; its thermal response is 285 K as seen in Table1 and indicated by its brown Colour in Figure5. The endothelium, when exposed to 193 nm of excimer laser for 2 ns, reported the lowest thermal response of 285 K, aligning with its thickness of 0.005 mm, thermal conductivity of 0.2 W/mK, and heat capacity of 3150 J/kg K. It presented the thinnest layer of the cornea.

Cornea

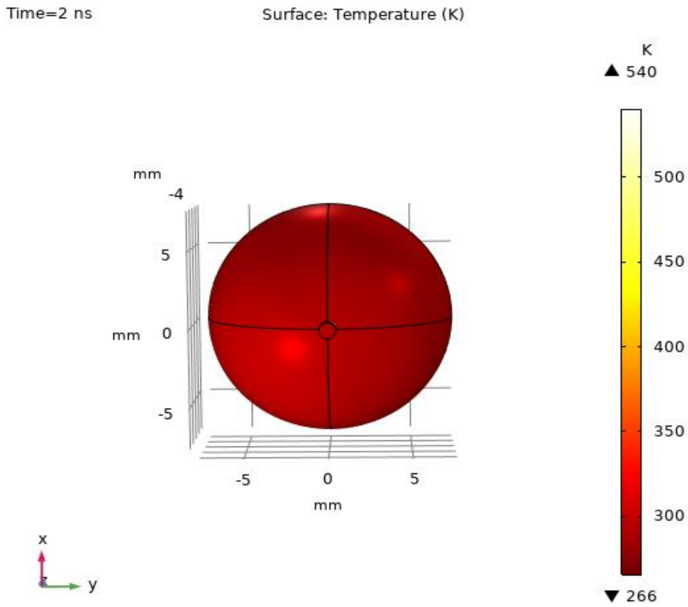

Figure 6: Thermal response of overall cornea exposed to 193 nm of excimer laser at 2 ns.

The total thermal response of the cornea reached 340 K when exposed to 193 nm of excimer laser at 2 ns, reflecting collective heat effects across all layers as seen in Table 1 and indicated by its brown-red Colour in Figure 6. This value is higher than the responses of individual layers due to the thicker cornea and its higher conductivity and heat capacity.

The significant thermal responses of the different layers of cornea, respectively, from outermost to innermost, were 300K, 295K, 330K, 290K, and 285K. Stroma is the thickest layer of the cornea and represents the highest values of heat (330K). Endothelium is the thinnest layer of the cornea; it represents the lowest value of heat (285K). This difference in values highlights that the thermal response of the tissue is influenced by certain elements, which are the thickness of the tissue, the thermal conductivity, and the heat capacity of the tissue. The increase in the thickness of the tissue, the thermal conductivity, and the heat capacity will increase the thermal response of the tissue, and vice versa.

Conclusion

It was found that different layers of the cornea have different thermal responses. The results demonstrate that the thermal response of each corneal layer is influenced by its thickness, thermal conductivity, and specific heat capacity. Stroma is the thickest layer of the cornea and represents the highest values of heat, equal to 330K; endothelium is the thinnest layer of the cornea; it represents the lowest value of heat, equal to 285K. These findings underscore the importance of considering individual layer properties when evaluating the impact of laser energy on the cornea, potentially contributing to improved clinical practices in LASER refractive surgery.

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