

Multiphysics Analysis of Red-Light Energy Deposition and Thermal Response in Ocular Tissues

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Abstract

Red-light photobiomodulation has received increasing attention for ophthalmic applications, including treatment of dry eye disease or meibomian gland dysfunction. Developing an accurate model capturing the interaction of red light with ocular tissues and corresponding thermal response provides a critical tool for the development of future ophthalmic photobiomodulation technologies. COMSOL Multiphysics was used to develop a computational model of energy absorption and transient thermal response of periocular tissues during extended exposure with an LED array operating at 640 nm. The model consisted of a full 3D head with skull, eyeball with segmented anatomy, and eyelid with parametrically controlled thickness. The Geometric Optics interface was used to perform ray tracing from each of the LEDs according to a specified angular distribution and power and the Radiation in Absorbing-Scattering Media interface computed light propagation into the tissue and the resulting spatially varying heat generation rate. The temporal evolution of tissue temperature including the effects of perfusion and heat transfer with the LED array and surroundings was handled with the Bioheat Transfer interface. Additionally, the power supplied to the LED array was modulated based on an IR sensor measurement of the eyelid surface temperature using the Events interface. The depth of thermal penetration and peak temperatures of critical tissue such as the cornea were found over a range of operating parameters and tissue properties. Specifically, the offset of the LED array from the surface of the eyelid, the eyelid thickness, and the optical properties (absorption and scattering coefficients) were found to have an influence on tissue heating. The modeling approach provides a framework for investigating light-tissue interactions and developing increasingly sophisticated computational representations of ocular systems.

Keywords: Photobiomodulation, Optical ray tracing, Bioheat transfer

Introduction

Dry eye disease afflicts approximately 10-20% of people over the age of 40 with prevalence on the rise due to an aging population and more widespread use of digital screens [1]. Affected individuals experience discomfort, partial loss of visual function, and impaired ability to perform daily tasks. In 2011, approximately \$3.8B per year was spent treating the condition with an estimated overall cost (including physician visits, loss of productivity, etc.) of \$55.4B [2]. An accurate model of light transport and thermal response in ocular tissues supports future research and development efforts in ophthalmic photobiomodulation.

Red-light photobiomodulation has been investigated for a variety of ophthalmic applications. However, the spatial distribution of

absorbed optical energy and the resulting thermal response within ocular tissues remain areas of active research [3]. The goal of this project was to develop a model to support research and development of ophthalmic therapies based on red-light exposure. During exposure, light absorption can heat the tissue and a model that can accurately quantify the spatiotemporal temperature distribution over the course of the exposure, provides a valuable tool for optimizing therapies.

A physics-based computational model was developed in COMSOL Multiphysics to predict the transient thermal response of tissue in the periorbital region throughout a 17 min exposure. The model utilized the Geometric Optics Module to compute the incident power density on the surface of the periorbital region and the Radiation in Absorbing-Scattering Media interface to resolve the penetration of light through the tissue depth and

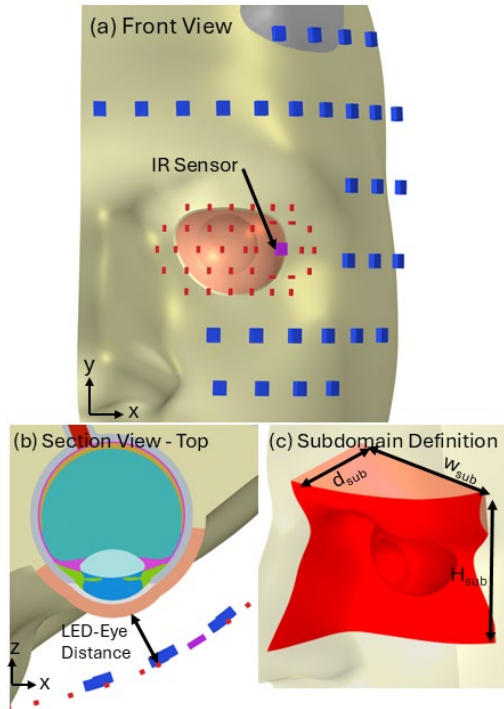


Figure 1. Geometry used for simulation (a) front view showing LED array (red and blue) (b) top-down section view showing the segmented eye anatomy and distance between the LED array and eyelid surface, (c) definition of subdomain for radiation transport

resulting volumetric heat generation. In a separate transient study, the heat source terms were used in the Bioheat Transfer interface to predict spatially and temporally resolved temperature distributions in the eyelid, cornea, and surrounding facial tissue.

Theory and Model Set Up

Geometry

The model incorporated anatomical geometry derived from a NIOSH headform [4], NIH skull model [5], and an anatomically representative eye model [6] as shown in Figure 1. Representative illumination sources and sensing components were explicitly modeled to capture the primary mechanisms governing optical energy deposition and thermal response.

The position of the LED array relative to the head was adjustable only in the z-direction to satisfy a user-specified perpendicular distance between the eyelid surface and closest LED as shown in Figure 1b. Additionally, the eyelid was modeled as a separate object with an adjustable thickness. Symmetry was assumed about the yz-plane,

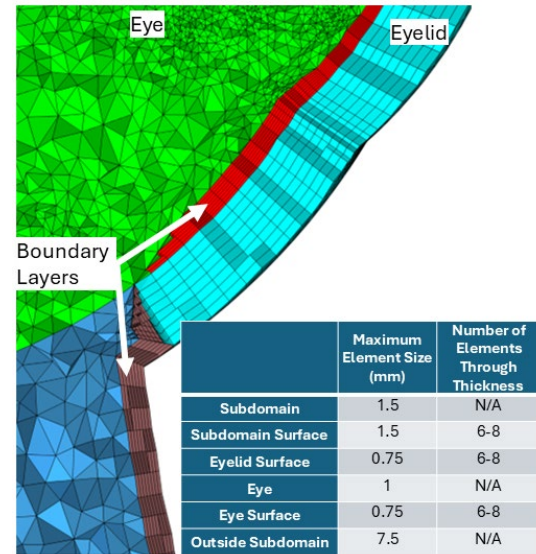


Figure 2. Mesh visualization on cross-section through eye and critical size control definitions.

allowing the model size to be reduced by a factor of 2. The geometry was partitioned to create a subdomain of the periorbital region in which the radiation propagation problem was solved.

Meshing

A large fraction of the light impinges on the eyelid and most of this light is absorbed creating a large gradient in the radiative intensity and heat generation rate. To sufficiently resolve the solution through the thickness of the eyelid without using an unnecessarily large number of elements, a relatively coarse triangular mesh on the eyelid surface (~ 0.75 mm) was swept to create 6-8 elements through the eyelid thickness. A free tetrahedral mesh was then used to mesh the remainder of the geometry with the element size controls indicated in Figure 2. Finally, a boundary layer mesh was applied to the face and eye surfaces.

Properties

The optical properties (absorption, μ_a , and reduced scattering, μ'_s , coefficients) of the different components of the eye anatomy were obtained from various literature sources [7-14]. The values of μ_a and μ'_s in the eyelid and soft tissue of the head are volume/thickness weighted averages of skin, muscle, and connective tissue as provided in Table 1 [16-18]. Three combinations of the averaged properties are used in the simulations bracketing the expected range of resulting heat generation rates. The lowest heat generation rate is expected for the

combination of lowest μ_a and highest μ'_s and vice versa. This approach provides a clean way to perform a bounding analysis on the degree of tissue heating.

Table 1. Combinations of absorption and reduced scattering coefficients used to represent expected low, medium, and high heat generation in homogenized soft tissue.

Tissue Designation	μ_a (cm ⁻¹)	μ'_s (cm ⁻¹)
Low	0.45	21.8
Medium	1.1	18
High	2.1	13.5

Thermal properties (specific heat, density, and thermal conductivity) of tissues were all assumed to be isotropic and taken from the IT'IS database [15]. Perfusion rates were also sourced from the IT'IS database.

Simulation Methods

The overall workflow of the simulation is provided in Figure 3 and described in detail in the subsequent sections.

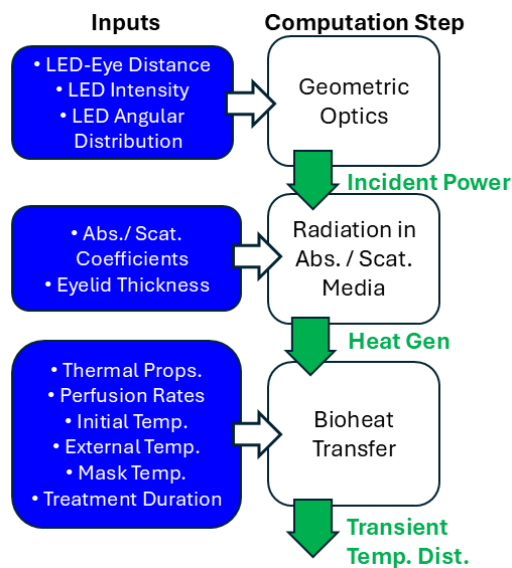


Figure 3. Flowchart showing steps of simulation process including inputs and key outputs for each step.

Geometric Optics (Ray Tracing)

The Geometric Optics module was used to trace rays of monochromatic red light (640 nm) emitted from the LEDs through the gap between the array and the face to compute the incident radiative flux distribution on the eyelid and facial surfaces.

The emitted power from each LED was computed from the *maximum* intensity and angular distribution reported in the manufacturer datasheets. The maximum intensity of the eye LEDs was 1100 mcd with a viewing angle of 60 deg, giving an emitted power per LED of 28.4 mW. The maximum flux of the face LEDs was 2900 mlm, giving an emitted power per LED of 23.6 mW.

The rays were released from the LED surfaces by defining the number of points to release from on each LED surface and releasing a specified number of rays (N_{rays}) from each of these points. The total power of the released rays was specified from the computation of emitted power from the above calculation. Higher number of release points (grid points) and number of rays provided more accurate and smoother results. A study was performed to determine the minimum values of these parameters so that increasing the values further do not appreciably change the observed incident flux on the eyelid. The incident flux was smoothed with the built-in smoother using a smoothing radius of 1 mm.

Radiation in Absorbing-Scattering Media

The incident flux from the ray tracing calculation was used as a boundary source for a volumetric radiation transport calculation within the tissue. This solved for the propagation, absorption, and scattering of the incident red light within the eyelid and eye tissue using specified tissue optical properties (absorption coefficient and reduced scattering coefficient). The absorbed radiation provides the volumetric heat source term for the thermal calculation.

The surface of the optical subdomain was specified as a semitransparent boundary with the external radiative intensity provided by the incident radiative flux from the ray tracing divided by π for the conversion to intensity. The S2 discrete ordinates method (8 directions) was used to discretize the angular directions in the radiative transfer equation. It was not feasible to increase to a higher order discrete ordinates method (DOM) because of the large domain size (despite the

reduction of the domain size to the subdomain defined in Figure 1c) and RAM limitations. However, most of the light was absorbed within a relatively shallow depth from the surface, so the low-order DOM is appropriate for this problem.

Bioheat Transfer

The transient Pennes bioheat transfer equation was solved to compute the spatially and temporally resolved temperature distribution in the tissue. The heat source term from the radiation absorption calculation was applied as a fixed volumetric source, enabling a one-way coupling that allows the thermal simulation to be run independently for different thermal conditions (e.g., body temperature, convection coefficients) without recalculating the optical sources. Blood perfusion was included as a volumetric heat sink term with tissue-specific perfusion rates.

In practice, the LED array is mounted on a surface that can heat due to resistive losses and also raise the temperature of the air. The temperature of the surface on which the LEDs are mounted and surrounding air were not explicitly modeled. Instead, their effects were captured using convection boundary conditions on the head boundaries. For the portions of the head not directly under the LED array, an adjustable convection coefficient, h_{ext} , and air temperature, T_{ext} , were used to model the heat flux at these boundaries. For the regions of the head directly under the LED array, the transient heating of the LED array and surface were accounted for. To do this, the portion of the face under the LED array was subdivided into 5 distinct regions, each with its own convection coefficient and external temperature. Experimental measurements of the LED array surface temperature over the duration of the 17 min exposure time were used to define the transient external temperature in each of these regions. The corresponding convection coefficient in each region was determined by $h_{ext,i} = k_{air}/d_i$, where d_i was the average distance between the LED array and the face for that region.

Temperature Control

In the center of the eye LED cluster (Figure 1a) is an infrared temperature sensor used to detect the surface temperature of the eyelid. This is used to modulate the power supplied to the LED array to maintain the eyelid temperature in a suitable

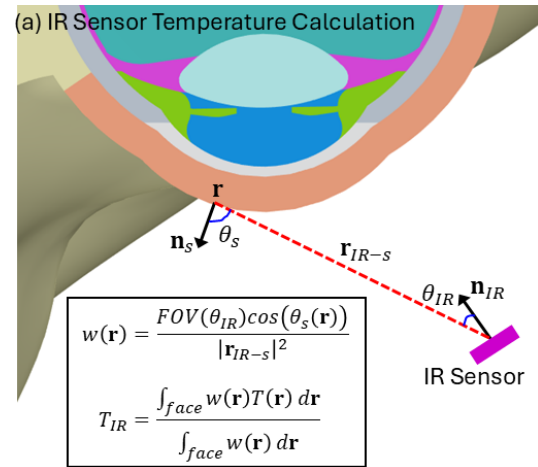


Figure 4. Weighted averaging of surface temperature used to represent the IR sensor in the model.

therapeutic range. When the detected temperature exceeds 42.5 °C, the LED power is reduced by 50% and when it exceeds 44 °C, the power is set to zero. This control logic is implemented in the model using the Events interface to set a fractional multiplier on the heat source term arising from light absorption.

To obtain an accurate representation of the temperature detected by the IR sensor, a weighted surface average was developed based on the distance between the IR sensor and eyelid surface and the relative orientation of the surfaces as depicted in Figure 4. This averaging procedure accounts for the change in the eyelid surface enclosed within the sensor field-of-view (FOV) as the distance of the LED array from the face is adjusted. Here the angular FOV function provided by the sensor manufacturer is implemented as an interpolation function in the model.

Comparison with Cadaver Measurements

Comparisons with human cadaver measurements were performed to evaluate consistency between simulated and experimentally observed thermal trends. In the cadaver studies, the eyelid thickness and distance between the LED array and face was measured at several points. Three thermocouples were placed underneath each eyelid and one on each eyelid surface. The LED array was operated at full power over a 17 min period with three runs completed for each specimen allowing the temperature to return to baseline between runs.

The LED-to-eyelid distance, eyelid thickness, and initial tissue temperature in the model were set

according to the measured values. The eyelid/soft tissue optical properties were set according to the observed skin tone of the specimen and perfusion rates were all set to zero. The comparison between model predictions and cadaver study results are provided in Table 2. Model predictions for the inside surface of the eyelid are within ~11% of experiment while discrepancy is somewhat larger for the outer eyelid surface with a maximum of 23%.

Table 2. Temperature increase after 17 min exposure in cadaver studies and corresponding model predictions.

Specimen	Inner Eyelid T Increase (°C)		Eyelid Surface T Increase (°C)	
	Exp.	Model	Exp.	Model
1	5.96	5.29	5.82	6.01
2	5.29	5.89	5.77	7.14
3	5.91	5.68	6.98	7.28

Results

A parametric study was performed to observe the variation in transient tissue heating with (a) LED-to-eyelid distance, (b) soft tissue/eyelid optical properties, and (c) eyelid thickness.

Using the baseline values of eyelid thickness = 2 mm, $\mu_a = 2.1 \text{ cm}^{-1}$, and $\mu'_s = 13.5 \text{ cm}^{-1}$, simulations were run with varying LED-to-eyelid distance from 1-2.5 cm. Figure 5 shows the peak and average cornea temperature for increasing distance. Above a distance of 2 cm, the activation of the temperature control system is not expected because the temperature detected by the IR sensor tends to remain below the 42.5 °C threshold. As a result the cornea temperature increases monotonically throughout the exposure and reaches peak and average values of 41.6 and 40.6 °C respectively. Further increasing the distance to 2.5 cm results in a 0.9 °C lower peak cornea temperature (40.7 °C) and 0.6 °C lower average cornea temperature (40.0 °C).

Using the baseline values of eyelid thickness = 2 mm and LED-to-eye distance = 1 cm, simulations were run with the low ($\mu_a = 2.1 \text{ cm}^{-1}$, $\mu'_s = 13.5 \text{ cm}^{-1}$), medium ($\mu_a = 1.1 \text{ cm}^{-1}$, $\mu'_s = 18 \text{ cm}^{-1}$), and high ($\mu_a = 0.45 \text{ cm}^{-1}$, $\mu'_s = 21.8 \text{ cm}^{-1}$) optical properties from Table 1. Figure 6 shows the evolution of the

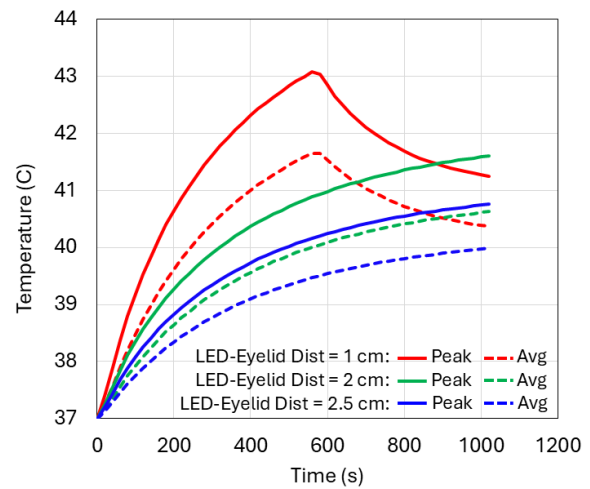


Figure 5. Peak (solid lines) and average (dashed lines) cornea temperature with eyelid thickness = 2 mm, $\mu_a = 1.1 \text{ cm}^{-1}$, and $\mu'_s = 18 \text{ cm}^{-1}$ with different LED-to-eyelid distances: 1 cm (red), 2 cm (green), 2.5 cm (blue).

peak and average cornea temperature over the course of the 17 min exposure for the 3 sets of optical properties. The temperature control system does not activate for the low or medium optical property cases because the temperature detected by the IR sensor remains below the 42.5 °C threshold. As a result the cornea temperature increases monotonically throughout the exposure for these cases and reaches a maximum value of 41.9 °C for the medium optical property case and 40.0 °C for the low optical property case. However, the temperature profile suggests the presence of an upper bound to the increase, as the rate of temperature rise progressively slows down, appearing to approach a stabilization toward a steady-state, likely due to the physiological heat dissipation mechanisms.

This total spread of cornea temperature over the range of optical properties considered is 3 °C for the maximum and 2.2 °C for the average (recall that the temperature is limited by the control system for the high optical property case).

The observed differences across optical property sets are consistent with the underlying light–tissue interaction mechanisms: lower absorption coefficients (μ_a) result in reduced conversion of optical energy into heat, leading to lower temperature increases, while lower reduced scattering coefficients (μ'_s) allow deeper light

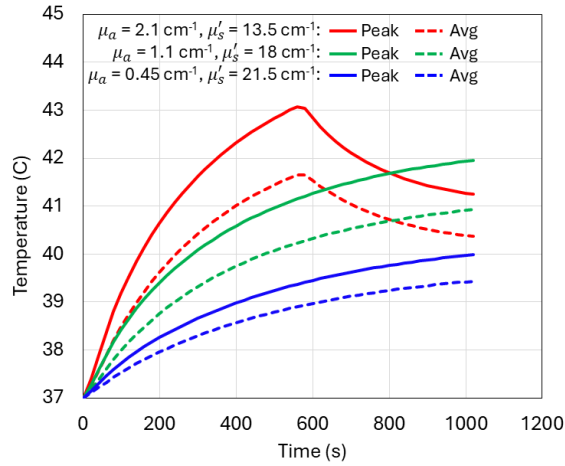


Figure 6. Peak (solid lines) and average (dashed lines) cornea temperature with eyelid thickness = 2 mm, LED-to-eyelid distances = 1 cm, and different optical properties: $\mu_a = 2.1 \text{ cm}^{-1}$, and $\mu'_s = 13.5 \text{ cm}^{-1}$ (red), $\mu_a = 1.1 \text{ cm}^{-1}$, and $\mu'_s = 18 \text{ cm}^{-1}$ (green), $\mu_a = 0.45 \text{ cm}^{-1}$, and $\mu'_s = 21.8 \text{ cm}^{-1}$ (blue).

penetration with less localized energy deposition. Consequently, cases with lower overall optical attenuation are associated with lower corneal temperatures.

Figure 7 shows the maximum and average cornea temperatures for eyelid thicknesses of 1.5, 2, and 2.5 mm with all cases having a LED-to-eye distance = 1 cm, $\mu_a = 2.1 \text{ cm}^{-1}$, and $\mu'_s = 13.5 \text{ cm}^{-1}$. The thermal response is similar for all cases with a couple of key distinctions. The primary driver for the difference in thermal response is that thicker eyelids provide higher thermal mass and thermal resistance at the primary heat source. This causes the local temperature at the eyelid surface to be greater for thicker eyelids, so that the IR sensor detects a higher temperature and causes the temperature control system to activate sooner for the thickest eyelid (at 420 s for 2.5 mm, 560 s for 2 mm, and 640 s for 1.5 mm). Additionally, the higher thermal resistance results in a lower peak cornea temperature (which occurs at the time the control system is activated). The effect is more pronounced for the thicker eyelid where the peak cornea temperature for the 2.5 mm case is $\sim 0.7^\circ\text{C}$ greater than for the 2 mm case. The peak temperature only differs by about 0.2°C between the 1.5 and 2 mm eyelid thickness cases.

The depth of thermal penetration into the eye and surrounding tissue is limited. The heat generation

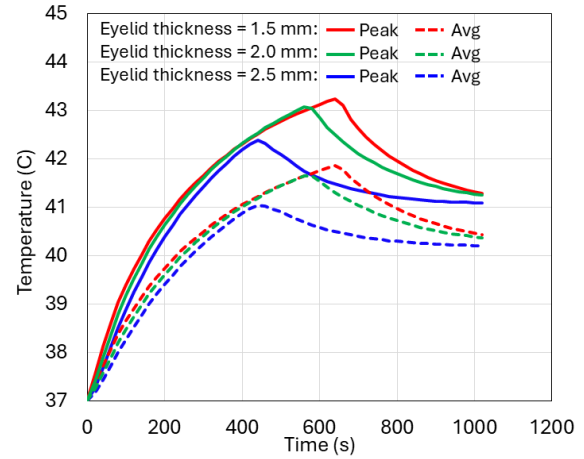


Figure 7. Peak (solid lines) and average (dashed lines) cornea temperature with eyelid thickness = 2 mm, LED-to-eyelid distance = 1 cm, and different eyelid thicknesses: 1.5 mm (red), 2 mm (green), 2.5 mm (blue).

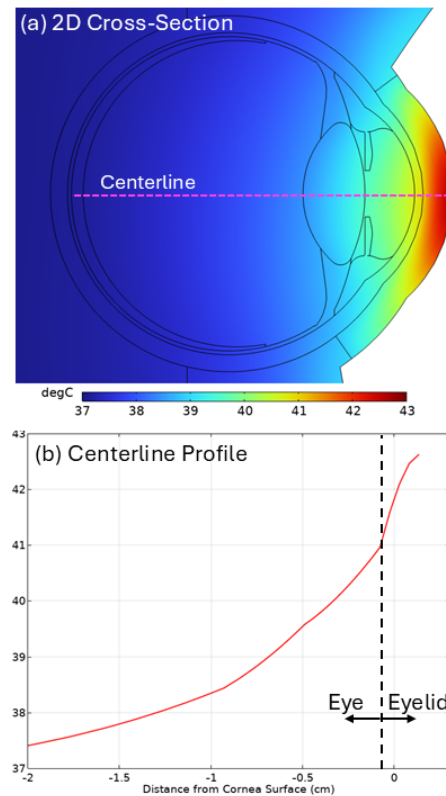


Figure 8. Depth profile of temperature in eye anatomy (a) cross-section and (b) line profile through center of eye

from absorbed light is concentrated near the tissue surface, particularly the closed eyelid, with the intensity decreasing exponentially with depth according to the tissue optical properties. Figure 8

shows representative thermal penetration profiles under conditions resulting in the highest predicted tissue temperatures.. These plots show that the thermal effects in the eyelid are highest and fall off rapidly deeper into the posterior sections of the eye.

Conclusions

COMSOL Multiphysics was used to predict the transient tissue heating produced by a red-light LED array. Comparisons with cadaver measurements provided confidence that the model captures the primary thermal trends associated with red-light exposure in ocular tissues. The model was then applied as a research tool to explore the effects of tissue properties and geometric variability on energy absorption and thermal distribution. The modeling framework provides a foundation for future investigations of ocular light-tissue interactions and the continued development of computational ocular digital-twin methodologies.

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