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Hui Sun
Ronald M. Kurtz
Tibor Juhasz

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Hui Sun,ª Ronald M. Kurtz,ᵇ and Tibor Juhaszᵇ,ᶜ
ªAlcon LenSx Inc., Aliso Viejo, California 92656
ᵇUniversity of California—Irvine, Department of Ophthalmology, Irvine, California 92697
ᶜUniversity of California—Irvine, Department of Biomedical Engineering, Irvine, California 92697

Abstract. In order to model the thermal effect of laser exposure of the iris during laser corneal surgery, we simulated the temperature increase in porcine cadaver iris. The simulation data for the 60 kHz FS60 Laser showed that the temperature increased up to 1.23°C and 2.45°C (at laser pulse energy 1 and 2 μJ, respectively) by the 24 second procedure time. Calculated temperature profiles show good agreement with data obtained from *ex vivo* experiments using porcine cadaver iris. Simulation results of different types of femtosecond lasers indicate that the Laser in situ keratomileusis procedure does not present a safety hazard to the iris. © *2012 Society of Photo-Optical Instrumentation Engineers (SPIE).* [DOI: 10.1117/1.JBO.17.7.078001]

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1 Introduction

Laser in situ keratomileusis (LASIK) is the most common refractive surgical procedure in the United States today. This procedure involves cutting a thin flap in the cornea either with a fine blade (microkeratome) or a femtosecond laser (so-called bladeless method) in order to expose the stromal bed.[1–4] Femtosecond laser systems have successfully entered the refractive surgery market, primarily due to their enhanced precision and minimized collateral tissue effects.[5–10] Diode pumped all-solid-state femtosecond lasers are now also commonly used or being investigated to perform additional procedures, such as corneal transplants and fs-lentotomy.[11–15] The improvement of the technology resulted in a progressive increase of the repetition emission frequency up to 60 and 150 kHz or even higher repetition rates.[16–18] One of the most popular commercial systems is the 60 kHz FS 60 Laser (AMO Inc., Santa Ana, CA). However, the higher repetition rate will increase the average laser power reaching both the retina and iris during LASIK surgery, raising the potential risk of thermal damage. Preliminary estimates suggest that almost half of laser energy passes beyond the cornea with potential effects on the retina and iris.[19–21] The temperature increase in human cadaver retina was investigated via *ex vivo* experiments and simulation by our group previously.[19] To study the temperature increase of the iris is also reasonable, since during the LASIK surgery the iris is closer to the focus of the laser beam than the retina. Although the iris does not absorb laser energy as strongly as the retina does, it is also pigmented and absorbs the laser energy. In order to model the laser exposure of the iris during femtosecond laser corneal surgery, we have developed a two-dimensional computer simulation using

the COMSOL finite element software (Comsol Inc., Burlington, MA). To validate our simulation results *ex vivo* experiments were performed using porcine cadaver iris where the temperature increase was measured by an infrared thermal camera. Different laser energies were used for both the simulation and the *ex vivo* experiments. The temperature of the samples was simulated and measured at every second throughout the 24 second long flap procedure. As the extension of the model, we also simulated the situation for other femtosecond laser systems, namely the 150 kHz iFS Advanced Femtosecond Laser (AMO Inc., Santa Ana, CA), the FEMTEC system (Technolas Perfect Vision Inc., Heidelberg, Germany), and the VisuMax system (Carl Zeiss Inc., Jena, Germany).

2 Materials and Methods

2.1 Finite Element Model

2.1.1 Basic assumptions

In the present study a finite element model was developed to simulate the temperature increase in porcine cadaver iris during the direct illumination by femtosecond laser pulses with the following assumptions:

(1) Although the real human iris consists of five cell layers, namely the anterior border layer, the stromal layer, the sphincter muscles fibers, the dilator muscles fibers, and the iris pigment epithelium, for simplification of the simulation the iris was modeled as one isotropic layer.[22] Based on our measurement the average size of the pupil was 4 mm and the diameter of the iris was 16 mm. A cross section of the iris was considered with a size of 6 mm in length and 300 μm

Address all correspondence to: Tibor Juhasz, University of California—Irvine, Department of Ophthalmology, Irvine, California 92697. Tel: +949 824-1148; Fax: +949 824-4015; E-mail: tjuhasz@uci.edu

in height. In order to simplify the calculation of spatially distribution of laser power, scanning was omitted since the tightly focused spot at the cornea will project a spot with more than a 1-mm diameter on the iris. More specifically, it was assumed that the laser had uniformly illuminated the entire iris sample because there are 60,000 laser pulses per second at different positions on the iris.

(2) An average refractive index of the tissue along the path of the laser beam was assumed to be 1.33 and any light scattering inside the iris was neglected since the size of the beam on the iris is more than 1 mm in diameter (compared with the focused 2 μm spot in the cornea), the fluence on the iris is 0.25 million times smaller than in the cornea, and therefore the microcavitation will not happen. We assumed that the iris and the flap are aligned parallel during the procedure due to corneal applanation by the patient interface and estimated the distance from the corneal surface to the iris to be 2.2 mm.

(3) Similarly to the retinal pigment epithelium, the high concentration of melanin pigments in the iris is the main factor for absorption of laser energy.[23] Therefore, it is reasonable to hypothesize that the spectral dependence of the absorption coefficient of the iris is identical to that of the retinal pigment epithelium. The center wavelength of 60 kHz FS 60 Laser is 1053 nm. The value of absorption coefficient for retinal pigment epithelium at wavelength 1053 nm is 100 cm^{-1}.[24] The reflectivity of the porcine cadaver iris is set according to Watts' data from pigmented rabbit iris. The value of reflectivity as measured in a spectroreflectometer at 1050 nm is 23%.[25]

(4) Three boundary conditions are provided by the commercial software: insulation, heat flux, and temperature. The upper surface of the sample was chosen for the heat flux boundary condition and other surfaces of the sample were chosen for the temperature boundary condition. The room temperature is set to 20°C for the boundary condition during simulation. The heat exchange surrounding the iris plays an important role as a boundary condition in the simulation. The heat transfer coefficient was chosen as from water to air and its value was determined according to Williams' experiment.[26] The equation for the heat flux boundary condition is

$$k\nabla h = h(T_{\text{inf}} - T), \qquad (1)$$

where k is the thermal conductivity ($W/m * k$), h is the heat transfer coefficient, and T_{inf} is the external temperature.

(5) The irradiance on the iris is 60 mW/cm^2 at 2 μJ laser pulse energy and 30 mW/cm^2 at 1 μJ laser pulse energy. The calculation of the heat absorbed by the iris was based on the Beer-Lambert law. The standard Beer-Lambert equation was rearranged to solve for the absorbed power. It is assumed melanin is uniformly distributed in the layers, and as such, that

the energy is absorbed uniformly within the iris. Also, any scattering that may exist inside the iris is not taken into account. Since the absorption coefficient derived from the retinal pigment epithelium is applied over the full thickness of the iris, it would certainly be a worst case assumption for the iris, resulting in predicted higher temperature numbers from the simulation.

2.1.2 Mathematical model

To develop the two-dimensional computer simulation the commercially available Comsol Multiphysics finite element software package was used. The heat transfer through the conduction and convection model was employed for the simulation. The time-dependent heat distribution in the model domain due to illumination laser pulses absorption is governed by the heat diffusion equation:

$$\rho C_P \frac{\partial T}{\partial t} + \nabla \times (-k\nabla T) = Q, \qquad (2)$$

where ρ is the density (kg/m^3), a value[27] of 1000; C_p is the heat capacity at constant pressure ($J/\text{kg} \cdot k$), a value[28] of 3997; k is the thermal conductivity ($W/m \cdot k$), a value[29,30] of 1.0042; and Q is the amount of laser energy absorbed by the tissue in unit volume per unit time. The equation provided above was solved by COMSOL finite element software for the finite element mesh and boundary conditions described above. Since the heat source term varies with laser pulse energy and we simulated the temperature increase at different laser pulse energy levels ranging from 1 to 2 μJ for 60 kHz FS60 laser and 150 kHz iFS Advanced Femtosecond Laser. In addition, we also modeled the temperature increase of the iris at laser pulse energy 1.4 μJ for the 40 kHz FEMTEC system and at laser pulse energy 0.3 μJ for the 200 kHz VisuMax system choosing the typical energy settings used in the clinical practice.[31,32]

2.2 Ex vivo Experiment

In our *ex vivo* study, the temperature increase induced by the 60 kHz FS60 Laser were measured by an infrared thermal camera (Ti55, Fluke Corporation, Everett, WA), detecting the emitted thermal emission over a spectral band from 8 to 14 μm, which is well separated from the 1053 nm laser wavelength.[19,21,33] We used twenty porcine cadaver irises with the normal brown pigmentation for the experiments, details can be found in our previous publications (see Refs. 21 and 34). To obtain the same beam diameter on the dissected iris in air as obtained with the numerical aperture of the FS60 Laser during actual surgery in the eye, we positioned the iris 1.5 mm from the focal point of the objective. The illumination time was 24 s and laser pulse energy was 1 and 2 μJ.

3 Results

Simulation results show the temperature distribution of the cross section of the iris for every second under the laser illumination for the 24 second long flap procedure performed by a 60 kHz FS60 Laser. The temperature of the iris before laser illumination was assumed to be 20°C. Two situations were modeled: laser pulse energy at 1 and 2 μJ. The temperature increases up to 1.23°C and 2.45°C, respectively. Figure 1 shows the simulation
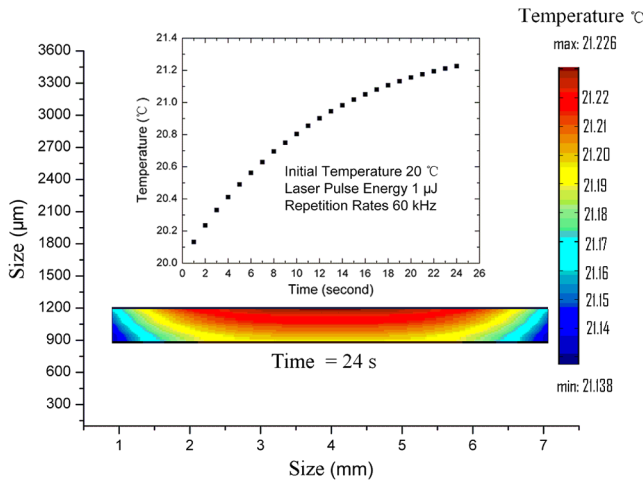
Fig. 1 Simulation of the temperature distribution inside the iris at 1 μJ laser pulse energy and 60 kHz repetition rate for 24 second flap procedure. Inset: The maximum temperature at the iris surface as a function of time calculated from the model.

Fig. 3 Comparison of the simulated values of the iris temperature rise with actual measured data of the iris temperature as a function of time for 1 μJ laser pulse energy and 60 kHz repetition rate of 24 second flap procedure.

of the temperature distribution in the cross section of the iris at 1 μJ laser pulse energy. The maximum temperature rise is 1.23°C, which is close to the measured mean temperature increase in the *ex vivo* experiment: 1.20°C ± 0.15 °C. The maximum temperature as a function of time at 1 μJ laser pulse energy is shown in the inset of Fig. 1. Figure 2 shows the simulation of the temperature distribution of the iris at 2 μJ laser pulse energy. The maximum temperature increase is 2.45°C. This result is in good agreement with the temperature measured by the infrared thermal camera in the *ex vivo* experiment: 2.30°C ± 0.14°C. The maximum temperature as a function of time calculated from the model is shown in the inset of Fig. 2. The advantage of the simulation is the ability to describe the temperature distribution inside the cross section of the iris which cannot be measured directly with an infrared thermal camera. The accuracy and predictability of the simulation was evaluated through the comparison of the results with the actual measured data. Figure 3 shows one of such comparison for one
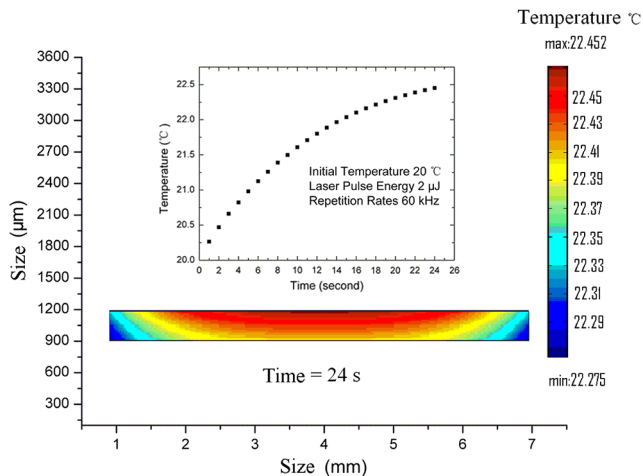
sample. It shows the comparison of the temperature increase as a function of time between the simulation and the *ex vivo* experiment in one sample at 1 μJ laser pulse energy. The temperature of the sample before laser illumination was used as the initial temperature in the simulation. Although the 60 kHz FS60 Laser is the most popular laser in the clinical practice today in the US, we also simulated the temperature increase for other commercially available femtosecond laser systems: 150 kHz iFS Advanced Femtosecond Laser (at pulse energy 1 μJ); 40 kHz FEMTEC system (at pulse energy 1.4 μJ); and 200 kHz VisuMax system (at pulse energy 0.3 μJ) using the same illumination time.[31,32] These results are shown in Fig. 4.

4 Discussion

Direct temperature measurement of the human iris *in vivo* is rather difficult; therefore, numerical simulations could be the best solution to investigate the potential thermal effect of LASIK surgery on the iris. Since the heat transport within

Fig. 2 Simulation of the temperature distribution inside the iris at 2 μJ laser pulse energy and 60 kHz repetition rate for 24 second flap procedure. Inset: The maximum temperature at the iris surface as a function of time calculated from the model.
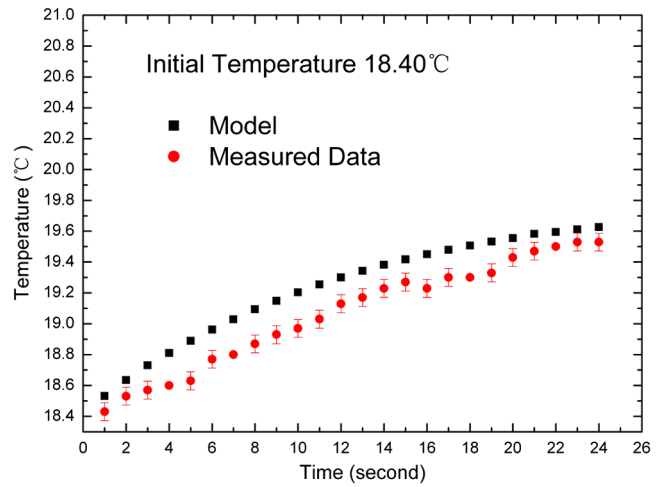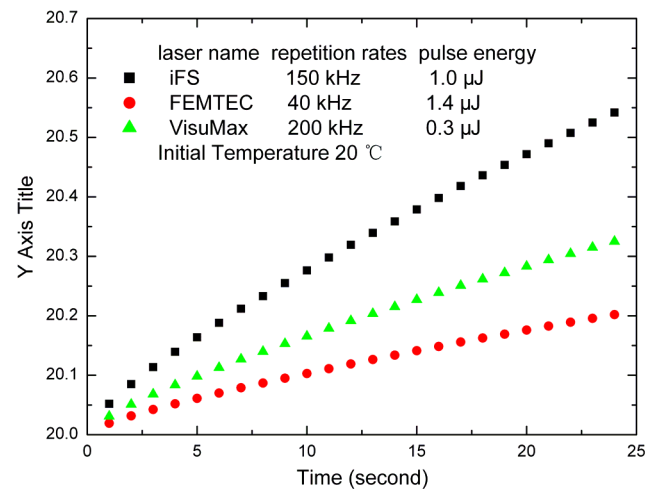

Fig. 4 Simulation of the temperature increase on the iris surface for three different laser system: 150 kHz iFS Advanced Femtosecond Laser, 40 kHz FEMTEC system, and 200 kHz VisuMax system.

the ocular tissue occurs mostly by conduction which can be precisely predicted by a heat conduction equation together with proper boundary conditions, a theoretical model to calculate the temperature increase at the tissue is particularly effective.[23,35] The finite element method is a powerful tool to calculate the intra-ocular temperature rise induced by laser illumination.[35–41] To date, a systematic study concerning femtosecond laser induced temperature increase in the iris is lacking. A two-dimensional computer model of the temperature field based on the heat-transport equation using the COMSOL finite element software to predict the temperature rise on the cadaver porcine iris exposed to femtosecond laser irradiation is described in this paper. Data from the *ex vivo* experiments indicate that all iris samples showed similar behavior when the same laser parameters were applied. Tissue properties, such as variability in pigmentation within the selected group, did not considerably influence the results and was ignored during simulation. The scanning can be neglected based on the following: for efficient flap cutting the laser is tightly focused into the cornea resulting in a transmitted beam with a diameter of approximately 1 mm on the iris; there are 60,000 laser pulses per second at different positions on the iris. To simplify calculations the scanning was neglected, more specifically it was assumed that the entire iris was homogeneously illuminated with the laser beam for 24 s. The reason for the lower measurements compared to the results of the model may be because the limitations of the two basic assumptions of no light scattering in the iris and uniform distribution of melanin absorbers. Simulation results indicate that at typical clinical energy settings (1 μJ laser pulse energy and 24 second procedure time), the temperature increase in the iris does not exceed 1.23°C. In an unlikely event that photo disruption does not occur (e.g., due to the laser beam distortions); the incident average pulse power may reach the 2 μJ laser pulse energy in the iris. Our model indicates that even in this worst case scenario, the temperature increase in the iris will not exceed 2.45°C at the end of the 24 second flap procedure time (including side cut procedure). It means that femtosecond laser corneal flap cutting does not present a hazard to the iris. The fact is that our model and measurements are perhaps the worst case scenario because the model and thermal camera measurements both have iris interface with the air but are not aqueous, as would be the case clinically. In fact, the actual temperature increase in an *in vivo* iris would be expected to be even smaller; since the surrounding aqueous humor and the local circulation may have a cooling effect.[42–44]

Ablation threshold of the porcine iris at 800 nm wavelength for a 150 fs-pulse-duration laser system was investigated earlier by Ngoi et al.[45] The effect of the 60 kHz FS60 Laser used in our studies during the flap cutting procedure is ten thousand times smaller than that of the laser radiation used in their study. Thus, the effect of such system is way below the photo-disruptive threshold, therefore, it did not cause any photo-disruptive damage in the iris. Although the current results were validated by *ex vivo* experiments for the 60 kHz FS60 Laser only, our simulation results showed that the other commercial femtosecond systems marketed for flap creation also provide similar data if the average power on the target and the total laser energy used for the procedures are similar in magnitude. Concerns about other types of laser injury to the iris, such as mutagenesis or altered cellular function, were not investigated in our study. However, the biological safety of the 1053 nm wavelength of the femtosecond laser has been well established.[46–49] Additionally, the relatively short illumination time also eliminates the possibility of mutagenesis or altered iris cellular function.

5 Conclusion

In summary, the theoretical and the *ex vivo* experimental studies discussed in this paper suggest that the flap cutting with the 60 kHz FS60 Laser used in LASIK surgery does not present a risk to the iris. Using this model we also suggest that other commercial femtosecond laser systems mean no thermal hazard to the iris.

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