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# THERMAL EFFECTS OF CORRECTIVE LASIK SURGERY

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***Abstract***
*In this paper we report a numerical, 3D finite element study on the thermal effects associated to the eye refractive laser surgery (LASIK) aimed at correcting the vision. To keep the problem tractable, the models are reduced to the cornea and aqueous humor regions. The main objective is the understanding of the heat transfer process within the cornea and its relation to the optical correction aimed by the LASIK surgical procedure. Several difficulties related to the lack of geometrical information and thermo-mechanic properties are commented. In this study we used FIDAP and GAMBIT as software tools*

***Keywords****: laser surgery, LASIK, heat transfe, finite element method (FEM)*

## INTRODUCTION

Eyes collect light and focus it, providing with vision. Ideally, we should see images that are sharp as a result of being focused on the retina. When an image gets focused in front of or behind the retina, the result is a blurry vision, and the abnormalities are called “refractive errors”: astigmatism, near-sightedness, and far-sightedness. Usually, contact lenses and eyeglasses are used to refocus images on the retina, restoring normal vision.

Refractive surgery is aimed at refocusing images onto the retina, by reshaping the cornea. Photo Refractive Keratectomy (PRK) and Laser Assisted *In-situ* Keratomileusis (LASIK) are used to reshape cornea by ablation. The main way that LASIK is different than PRK is that LASIK creates a small flap in the cornea before reshaping it. The flap is placed back over the reshaped cornea, decreasing the symptoms of pain and itching in the eye. Remarkably, seventy percent of patients who undergo LASIK end up with 20/20 vision.

It is of crucial importance to cut-off the laser beam after a precise time, or damge to the eye may occur. Numerical simulations may help in planning LASIK and in assesing the colateral effects that accopany this surgery. In this paper we present a FEM study of the thermal effects associate to LASIK procedure.

## MATHEMATICAL AND NUMERICAL MODELS

The heat transfer problem associated to LASIK procedure is modeled by the *energy equation*

$$\rho c_p \left[ \frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T \right] = k \nabla^2 T \,, \qquad (1)$$

where $\rho$ is the density, $c_p$ is the specific heat, $\mathbf{u}$ is the velocity field (in the aqueous humor, when considered a fluid region), $k$ is the thermal conductivity.

When the aqueous humor is considered a fluid region, the thermally induced flow at moderate heat input is considered laminar, incompressible, governed by the *momentum* (Navier-Stokes) law

$$\rho\left[\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\cdot\mathbf{u}\right]=-\nabla p+\mu\nabla^2\mathbf{u}+\rho\mathbf{g}\,, \tag{2}$$

and by the *mass conservation* law

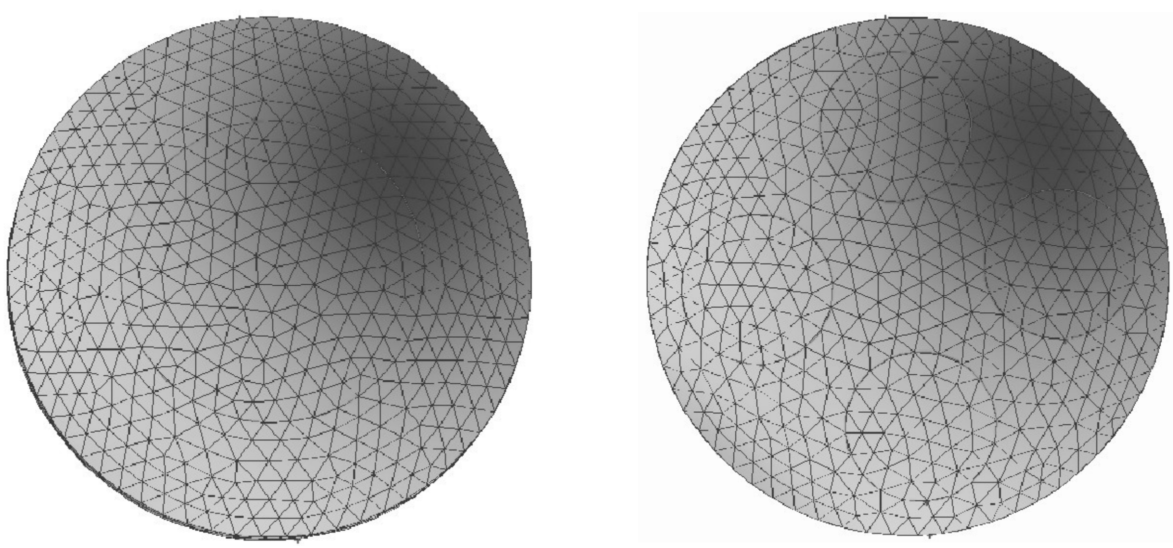
$$\nabla\mathbf{u}=0\,. \tag{3}$$

Here, $\mu$ is the dynamic viscosity, $p$ is the pressure field and $\mathbf{g}$ is the gravity – as the patient would be generally laying (horizontal position), $\mathbf{g} = g\mathbf{k}$, where $\mathbf{k}$ is the unit vector in vertical direction.

The temperature field within the eye is initially uniform, at 37°C, and the aqueous humor is at rest (i.e., no flow). We used the folowing for the cornea: $\rho$ = 1060 kg/m$^3$; $k$ = 0.628 W/m$^2$K; $c_p$ = 4187 J/kg·K, and for the aqueous humor: $\rho$ = 1000 kg/m$^3$; $k$ = 0.5 W/m$^2$K; $c_p$ = 4187 J/kg·K; $\mu = 7.8\cdot10^{-3}$ N·s/m.

The boundary conditions: prescribed heat flux on the surface facing the laser beam, and thermal insulation on the rest of the boundary. The ambient temperature is assumed $T_a$ = 20°C. For the flow part of the problem (when the humor is considered a fluid body), no-slip boundary conditions are imposed at the walls that contain the aqueous humor.

The geometry and FEM mesh (tetrahedral, unstructured mesh that comprises hexahedral and pyramidal elements) were produced by GAMBIT. Then, we used FIDAP to solve the problem. Grid-independent solutions were obtained by accuracy tests performed on the temperature field. Figure 1,a shows the FEM mesh used for the "static" procedure, where the laser beam is coaxial with the cornea; we simulated the 2, 3 and 4 mm laser beams – the 4 mm laser beam is presented in figure.



**a.** Fix beam model **b.** Equivalent, rotational beam model

**Fig.1** FEM meshes for 3D simulations

The aqueous humor is here a solid body. The cornea base-plane is maintained at 37°C. We focused on the dynamics of the heat transfer process for the reaching the threshold temperature of

59°C, for different values for cornea density. This limit is safe, and prevents harming the eye.

## RESULTS AND DISCUSSION

Figure 2 shows the time needed to reach 59°C as a function of cornea density for a single beam laser of 0.644 W and 2, 4, and 4 mm radius, in myopia correction. The aqueous humor is a solid body. Figure 3 shows the same time (to reach 59°C) as a function of the density and consistency (fluid and solid) of the aqueous humor.

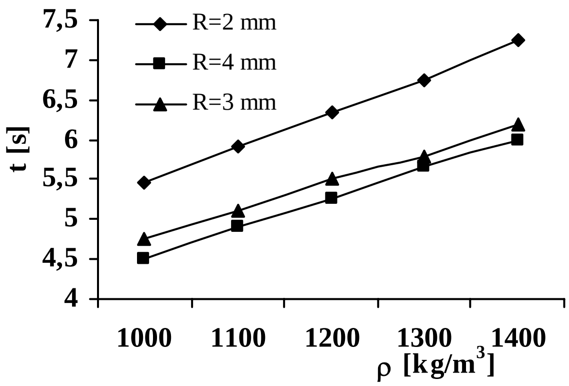



**Fig.2** The time to 59°C in single 0.644W beam myopia correction, as function of density and laser radius.

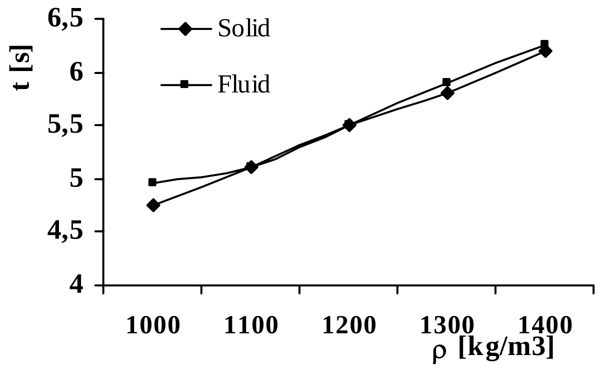



**Fig.3** The time to 59°C in myopia correction for solid and fluid humor; a single, 0.644W, 3 mm laser beam.

Figure 4 displays the time to 59°C as a function of aqueous humor density in hypermetropya for a four beam 0.644 W laser. We simulated both liquid and solid humor. Cornea base plane is at 37°C. Figure 5 gives the time to 59°C as function of laser power, in myopia correction. Cornea density is 0.628kg/m3 and the thermal conductivities are those common to tissue and cornea. In this simulation a 2 mm laser was assumed, and the humor is solid.

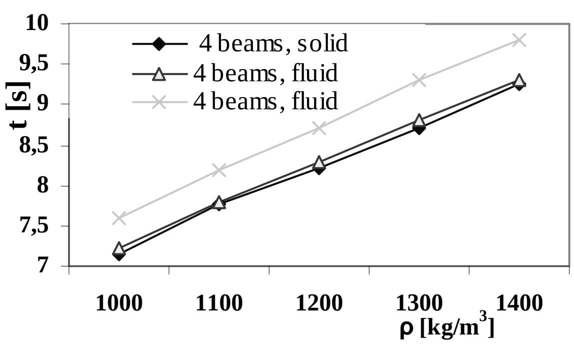



**Fig.4** The time to 59°C as function of density, in the 4 beam 0.644W laser procedure.

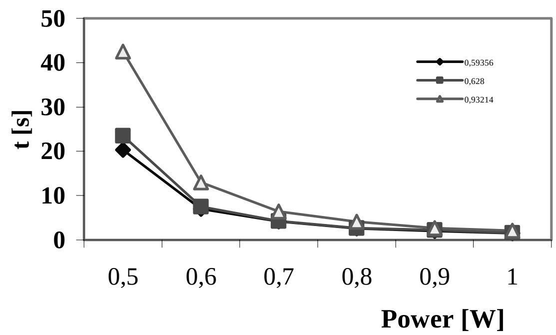



**Fig.5** The time to 59°C as function of laser power, in myopia correction.

Figure 6 shows the temperature field for single and four beam LASIK procedures. The mesh used to simulate the LASIK procedure with rotational beam, when the beam has circular motion about the axis of the eye. The difficulty of modeling a dynamic (movable) boundary condition was alleviated by assuming four, symmetrically spaced, static beams.

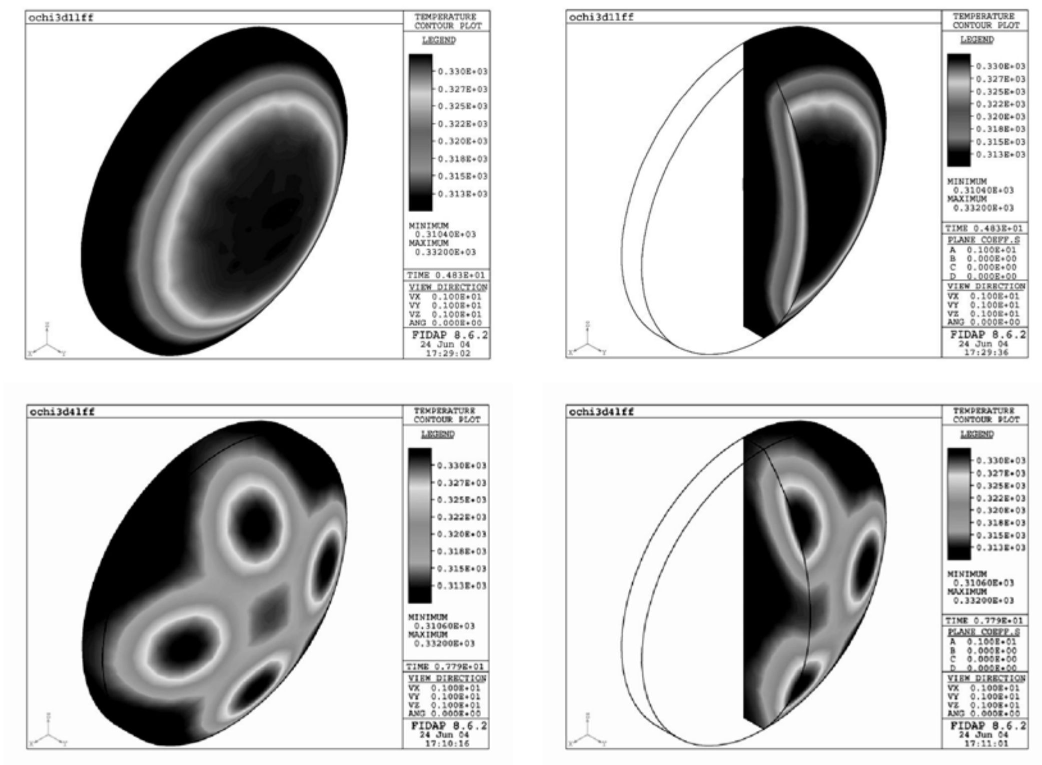



Fig. 6 Temperature field at 59C for single and four beams LASIK

## CONCLUSIONS

In this paper we report several simulation results concerning the thermal effects that accompany the corneal corrective laser surgery. The main conclusions are as follows:

- The time to 59°C increases linearly with corneal density. The results for 3 and 4 mm beams (large, but increasingly used in the current practice) are close.
- The time to reach the threshold temperature increases with the optical zone size and decreases for increasing laser power.
- The times to 59°C for the aqueous humor solid and fluid models are close.
- The assumed values for the properties of the different regions were collected from literature. Better estimates are needed fore accurate results that may help surgery.
- For small power lasers and small values for corneal density the time to 59°C is sensitive to the boundary condition type assumed for the aqueous humor base plane. This suggests that more complex models, which would include the regions beneath the aqueous humor base-plane should be used for accurate results.

### Acknowledgement

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