MODELING INTRASTROMAL PHOTOREFRACTIVE KERATECTOMY PROCEDURES

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Abstract- **The main idea to correct sight disorders using lasers is to modify corneal curvature by applying laser to specific layers of the cornea. Intrastromal Photorefractive keratectomy is a laser technique used to correct sight disorders by evaporating corneal tissue, which results in small cavities that may coincide to form a larger cavity that will collapse to deform the curvature of the cornea. In this work, a 3D finite element model of the cornea was designed with typical parameters to simulate the procedure. The model outcome was compared with an earlier 2D model used for the same purpose, so as to determine its accuracy. Finally, a 3D finite element simulation of the procedure was made for a virtual astigmatic case, so as to visualize the corneal curvature change. The results of this work show that this finite element model is relatively accurate for modeling the corneal deformation after performing the procedure.**

***Keywords* - ISPRK, Photorefractive Laser Surgery, Picosecond Laser, Femtosecond Laser, Finite Element Modeling, Biomechanics.**

I. INTRODUCTION

Intrastromal Photorefractive keratectomy (ISPRK) is an interesting and challenging technique for refractive corneal surgery that has emerged at the beginning of the 1990s. Removal of tissue in the corneal stroma is performed by using a pulsed laser beam which is sequentially focused to individual spots at a plurality of points in the stroma. A single layer of tissue is removed by steering about 10 μm focal spot in a spiral pattern. The spots layers are arranged in successive spiral patterns to photo ablate and remove a plurality of layers of stromal tissue, with the diameters of the layers being properly sized to result in the desired diopter correction [5]. Photo ablation has either a continuous disk-shaped for correcting myopic cases, or a ring-shaped cavity that is generated to correct hyperopic cases. When the gaseous vapor inside the cavities created is diffused into the surrounding medium, the cavity collapses. It is expected that the removal of stromal tissue then induces a stable change in curvature of the anterior corneal surface. The main advantage of this technique is that the original layers of epithelium and Bowman's membrane are not injured, which is not the case with Excimer laser surgeries. Thus, the stability of the cornea is less affected, and corneal haze is less likely to occur [8].

According to a previous study [7], endothelial damage does not occur if the focus of the laser beam is placed at least 150 μm away from the endothelium. In practice, however, it has been difficult to precisely and uniformly create intrastromal cavities using picosecond intrastromal ablation. Histological data performed on some eyes revealed a compartmentalized pattern of ablated tissue. Therefore, early clinical trials of picosecond intrastromal refractive surgery indicated some lack of control over the refractive results [7].

A new approach in photorefractive surgery is intrastromal ablation using femtosecond laser, also referred to as an ISPRK surgery; first clinical results were obtained in 2003. It showed that after surgery the treated corneas were highly transparent and refractive results were stable. This technique and other several different techniques for refractive surgeries are now under investigation [6].

Extensive theoretical models have been proposed for this kind of surgery, especially using the algorithm of finite elements, that certain predictions can be made concerning any changes in refraction [8]. The method of finite elements is a very powerful tool of modern engineering science for modeling biomechanical problems.

Previous models that used the finite element method include the model created by Hennighausen and Bille [3]. They created three finite element models to predict corneal curvature change after an ISPRK surgery, and the results of the three models were compared. Their models differed essentially in the underlying assumptions about the mechanical behavior of the cornea. Another model developed by M.R. Bryant, V. Marchi, and T. Juhasz [1]. They compared their finite element model results with a geometric model regarding clinical data. Both of the models have an error of about 20% compared with the clinical data. Another similar finite element model that is used to calculate refractive power change induced by LASIK surgery has been created by C. Deenadayalu, B. Mobasher, S.D. Rajan and G.W. Hall [2]. They studied the effect of changing the flap dimensions, IOP (Intraocular pressure) and modulus of elasticity on model results that was essentially concentrating on hyperopic cases.

In this work, a 3D finite element model for the cornea is presented, with typical dimensions, material properties, boundary conditions and loads. Model outcomes were compared with an earlier 2D model [1], to determine its accuracy. A 3D finite element simulation was also made for the procedure for a virtual astigmatic case to visualize the effects on corneal curvature and shape.

II. METHODOLOGY

The finite element modeling method was used in this problem as it has the capability for incorporating biomechanical properties. It is more advantageous than the finite difference method as it uses elements rather than a rectangular grid that provides a much better approximation for the irregularly shaped objects, as in our case here.

A. Model description

The finite element model block diagram is shown in Fig. 1.

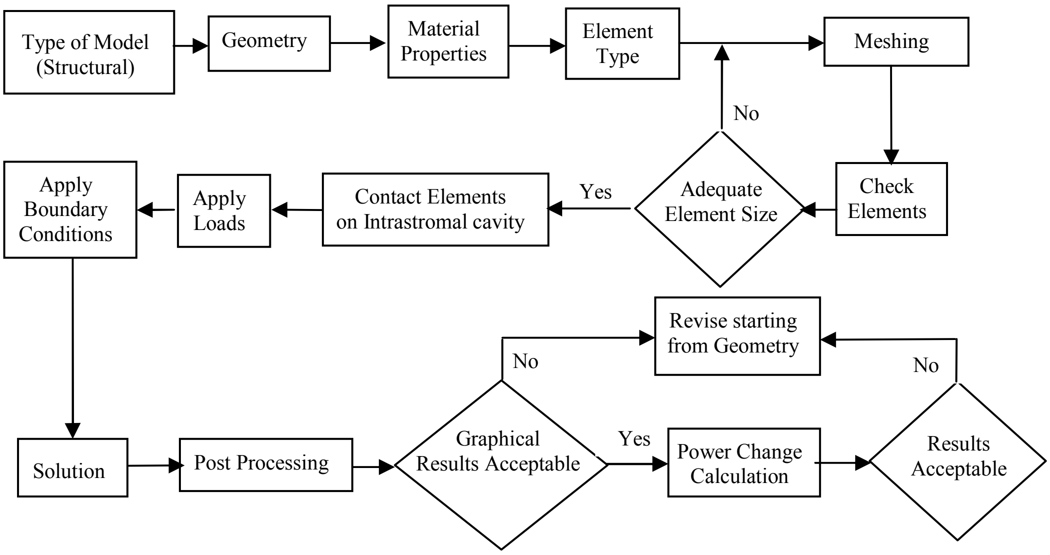

Fig. 1. Block diagram of corneal modeling.

The model was based on the following assumptions:

1. Axisymmetric three dimensional model.
2. Isotropic incompressible material, with exponential elastic stress-strain relationship for the cornea.
3. The cavity collapse control was performed using contact and target elements (contact pair) on the cavity's posterior and anterior surfaces, respectively. The contact pair was set to close the intrastromal cavity and allow sliding between the closed surfaces.
4. Fixed boundary conditions at the limbus, with internal intraocular pressure of 15 mmHg as being the load.
5. No temperature effects were included in the model.
6. The model was implemented using ANSYS version 10 (ANSYS Inc., Canonsburg, South Carolina, USA).

The modeling process was started by determining the physics of the problem, which was a structural problem, and then the corneal geometry and material properties was entered to the model. After that a suitable element type was selected that was used in the meshing step. The quality of the elements in terms of size and fitness to the cornea was tested and checked. Then a contact pair was created between the intrastromal cavity surface's elements, so as to ensure that the elements did not overlap upon collapse of the cavity. Following that, the intraocular pressure load and the boundary conditions was applied to the corneal model. Thus the solution phase was begun in which nodal displacements were calculated. After that the graphical results were displayed and checked regarding nodal displacement profile to be logically acceptable and contact pair status to be fully closed. The corrected corneal refractive power was then calculated and compared with a reference corneal power, which is the power before laser treatment. After the final results were obtained, they were checked and if they were unacceptable we had to get back to the 'geometry' block, and review everything and make necessary adjustments, especially with regard to the contact elements attached to the cavity elements, in terms of the full closure of the cavity.

B. Modeling myopic cases

In order to calculate the postoperative corneal radius of curvature, the finite element model output was used. The nodal postoperative displacement, which was the primary output of the model, was added to the old nodal coordinates to get the new nodal coordinates (X_p, Y_p).

Then the curve fitting method was employed to fit a circle with radius R on the central nodes. Only the central 3 mm of the cornea were evaluated, as this zone was considered to be the optical zone that the light passes through to reach the retina. The used curve fitting equation was as follows:

$$F = \sum_{i=1}^{n} [R^2 - [(X_{pi} - a)^2 + (Y_{pi} - b)^2], \tag{1}$$

where a, b are constants representing the center of the fitted circle. Substituting R into the next relationship gives the postoperative corneal power in diopters, D_p:

$$D_p = \frac{(n-1)}{R} = \frac{0.376}{R}, \tag{2}$$

where n is the corneal index of refraction. The corneal power change was:

$$\Delta D = D_p - D. \tag{3}$$

Where D was the reference value of the corneal power resulting from running the previous model, but without taking the intrastromal cavity into consideration.

The previously described finite element model was used to simulate and predict the outcome of treating myopic cases with ISPRK. Fig. 2 shows the corneal model after completing the preprocessing phase. The concentrated elements at the center of the cornea resulted from filling the irregular intrastromal cavity with elements to fit the boundaries in a good way.

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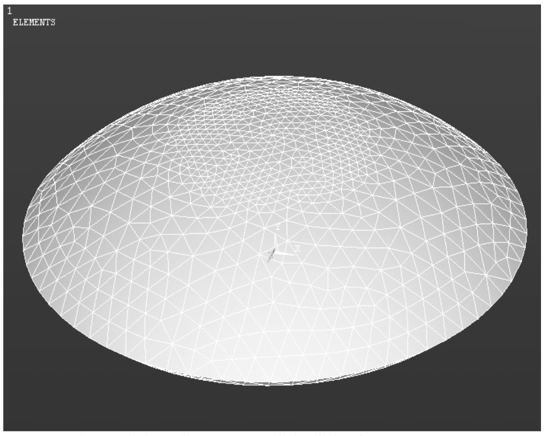

Fig.2 Finite element model of the human cornea

C. Modeling astigmatic cases

The finite element model was used to simulate and predict an astigmatic case combined with myopia. A virtual case was created in which 7.4 diopters of power difference between two perpendicular corneal meridians in the X and Z directions. The cornea also has a myopic effect of about 7 diopters that needed to be corrected. An intrastromal cavity was proposed to correct that case with dimensions based on the general rule of thumb used by some eye laser surgeons, that every one diopter of myopia is treated with about 13 μm of ablation depth [4]. In addition, the cavity was oriented so that the weaker power meridian of the cornea was opposing the more power correcting meridian of the cavity.

Calculating the postoperative power change was based on the same method used in calculating power for myopia, except that the corneal radius of the curvature was obtained in two directions, X and Z. The nodes in the central 3 mm zone were also considered in the calculations. The curve fitting equations in this case were:

$$F_1 = \sum_{i=1}^{n} [R_x^{\,2} - [(X_{pi} - a_1)^2 + (Y_{pi} - b_1)^2],$$

$$F_2 = \sum_{i=1}^{n} [R_z^{\,2} - [(Z_{pi} - a_2)^2 + (Y_{pi} - b_2)^2]. \qquad (4)$$

Here a_1, a_2 and b1, b2 are constants representing the centers of the fitted circles. Substituting R_x and R_z in the next equations gave the postoperative corneal refractive powers.

$$D_{xp} = \frac{(n-1)}{R_x} = \frac{0.376}{R_x},$$

$$D_{zp} = \frac{(n-1)}{R_z} = \frac{0.376}{R_z}. \qquad (5)$$

The corneal power changes in the X and Z directions were:

$$\Delta D_x = D_{xp} - D_x\,,$$

$$\Delta D_z = D_{zp} - D_z. \qquad (6)$$

And the astigmatic power correction was:

$$\Delta D_{ast} = D_{xp} - D_{zp}. \qquad (7)$$

III. RESULTS

A. Myopic model

Fig. 3 shows the displacement profile of the anterior surface of the cornea, which was minimum at the limbus and maximum at the part facing the cavity border inside the cornea, and then lower displacement was observed at the center part. This profile is the main idea behind any photorefractive eye surgery, as it causes the corneal radius of curvature to be bigger, and decreases the corneal power to correct myopia. Running the model with three different intrastromal cavity dimensions resulted in Table I. The three groups of cavity dimensions and corneal power changes were the average of 10 clinical cases. They were used to compare the outcome of the model with a 2D finite element model used for the same purpose, where the 2D model and the clinical data were obtained from a previously published work [1].

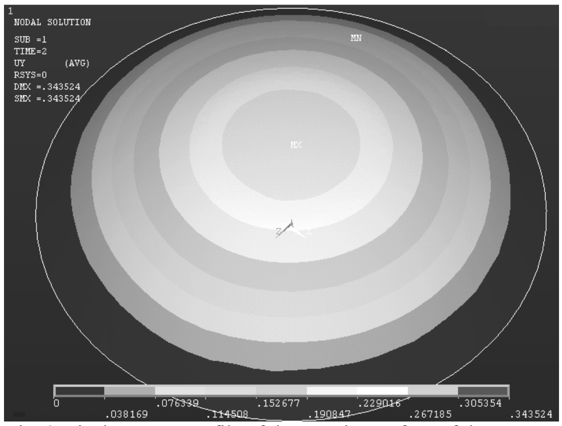

Fig. 3 Displacement profile of the anterior surface of the cornea.

TABLE I
Model Trials

	Cavity diameter in mm's	Cavity thickness in μm's	Power change in Diopters	2D model (Error) in Diopters	3D model (Error) in Diopters
1	4	100	11.3	14.5 (3.2)	11.7 (0.4)
2	4	120	13.083	16.7 (3.617)	13.0 (-0.08)
3	3.2	120	19.6	22.5 (2.9)	19.0 (-0.6)

B. Astigmatic model

Fig. 4 shows the displacement profile of the anterior surface of the cornea after running the model. This profile presented the idea behind treating astigmatism, in which two corneal meridians are deformed with different degrees, so that corneal power is changed differently at those meridians.

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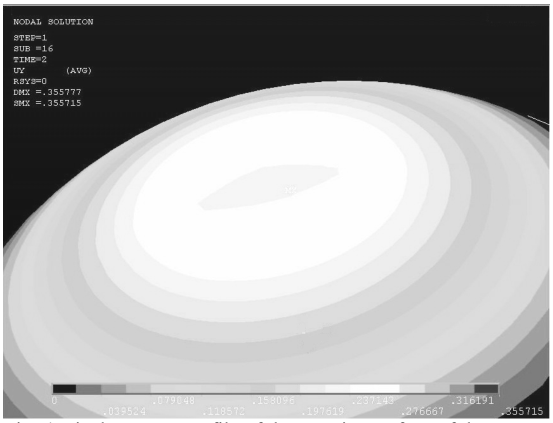

Fig. 4 Displacement profile of the anterior surface of the cornea having astigmatism treated.

The outcome of the astigmatic myopic case model was calculated using equations 4 through 7. The corneal power in the X and Z directions were calculated before and after applying the cavity effect and ΔD_{ast} was found to be 2.13 diopters.

IV. DISCUSSION

A. Myopic model

Comparing the results with the 2D finite element model showed that our model is more correlated to the clinical data, with a smaller percentage of error, about 2.5 % of average error compared to 23.5 % for the 2D model. The main reasons behind that improvement in results were the followings:

1. Using contact and target elements to control the cavity collapse event during the run of the model, instead of using gap elements between the surfaces of the cavity. The main advantages were having a surface to surface contact pair, not a node to node one, and the absence of any need to determine a gap element stiffness value that could result in improper behavior.
2. Creating a 3D model, so no approximations were made regarding the affecting pressure. That means that the pressure on the posterior surface of the cornea was applied with the same clinical value of 15 mmHg in the model. This was not the case with the 2D model, which used the shell theory to model pressurized objects, and in that case pressure was applied on a line not an area.
3. The approach used to create the cavity shape inside the stroma. Both approaches were mentioned in the ISPRK United States Patent [5]. The geometric model guided one was used by the 2D model, and the corneal curvatures averaging guided one was used in this 3D model.
4. Using a different value for the index of refraction of the cornea that can be found at the references, and incorporating corneal density into the model as an additional material property.

B. Astigmatic model

We noted that the myopic correction was nearly achieved, with only a shift of 0.1 diopters from the target value of 7 diopters in the X direction. And for the astigmatism correction there was a bigger shift of 2.13 diopters from the target value of zero diopters, which is the pure normal spherical case for the cornea. This indicated that an overcorrection occurred for the astigmatism effect correction, which needs to be modified regarding the intrastromal cavity thickness in the Z direction by making it thinner in that direction. This demonstration of the model for that type of clinical cases showed the usefulness and importance of the model as a preoperative predictive tool and as planning guide.

V. CONCLUSION

In conclusion, an accurate finite element model used for simulating myopic ISPRK procedures was created and tested. Based on the comparison of the model predictions with actual clinical data, it was shown that this type of procedures can be predicted, taking into consideration the related factors affecting corneal power changes, such as the intraocular pressure, specific material properties for individual cases and other factors. This work showed that astigmatism can also be modeled and predicted by using nearly the same myopic model outlines. A virtual astigmatic case was introduced to illustrate the model, and used to evaluate the suitability of a proposed intrastromal cavity shape.

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