Patient-Specific Finite Element Simulations of Standard Incisional Astigmatism Surgery and a Novel Patterned Collagen Crosslinking Approach to Astigmatism Treatment

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Introduction

Finite element analysis has been explored as a tool for estimating the refractive outcomes of corneal interventions such as laser

in situ keratomileusis and photorefractive keratectomy [1]. Corneal astigmatism is a common geometrical abnormality that can be quantified topographically as the difference in curvature or dioptric refractive power of the steepest and flattest meridians, often represented as simulated keratometry values. Astigmatic keratotomy (AK) is an incisional method for correcting astigmatism by placement of paired, peripheral corneal arcuate incisions along the steep axis of astigmatism that act to flatten the steep axis. AK is a convenient method of astigmatism correction, but it is less predictable than other surgical options, has a limited range of effect, can induce higher-order corneal aberrations that reduce visual acuity, and can destabilize the cornea due to its dependence on disruption of collagen lamellar continuity [2].

Corneal collagen crosslinking (CXL) is an alternative method for minimally invasive corneal refractive alterations through augmentation of corneal material strength. The current clinical implementation of collagen crosslinking involves broad treatment of the corneal surface with UV_A irradiation after imbibitions of photosensitizing riboflavin solution and is directed primarily toward the stabilization of corneal ectasia. Previous finite element analyses from our group have explored the relationship between the stiffening effect of CXL and changes in corneal curvature [3] and have studied candidate patterns for a novel method of astigmatism treatment using CXL. The goal of this study was to compare the simulated corneal topographic effects to a standard incisional approach to astigmatism treatment to patterned CXL [4].

Methods

In vivo human corneal astigmatism data was obtained using a Scheimpflug tomography system (Pentacam v.1.61) in one patient. The data was fit to a 12th order Zernike polynomial and extrapolated accordingly. The extrapolated data was imported into Solidworks (ver. 2011) to construct the 3D geometry. We used an empirical spherical sclera with a thickness of 1 mm and outer radius of 10.5 mm. The obtained 3D geometry was meshed using a commercial mesh generator (Truegrid, v. 2.3.4) with hexahedral elements. A nonlinear, anisotropic, hyperelastic material

Fig. 1 Axial curvature maps of pre- and post-treatment cornea

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formulation was used in the finite element model. The fibrillar forces were accounted for in the model for two orthotropic directions (nasal-temporal and superior-inferior). Intraocular pressure was specified to physiological levels (15 mmHg). Three different simulations were run for each treatment procedure by using ABAQUS (v. 6.11). The prestrains and the accurate node positions were calculated by pursuing an iterative method [5] prior to the surgical modifications.

Surgical Simulations. We compared the AK incision-only model, collagen crosslinking model, and AK incision + collagen crosslinking model. AK incisions were made on the steep axis of the astigmatism as two symmetric 45-degree arc incisions 150 microns wide and a depth of 90% of the patient-specific corneal thickness at the 7-mm diameter arc. A crosslinking treatment was applied to the flat axis of astigmatism. The model was solved for the following cases: AK incision only, bowtie-patterned CXL only, and combined AK and CXL. Corneal nodal surface coordinates were used to quantify the astigmatism in the postoperative (postsimulation) stage. The exported coordinates were used to calculate the axial elevation and instantaneous curvature data by a custom FORTRAN routine. The calculated data was imported into corneal topography reader VOL software (v.7.42) to obtain the topographical maps.

Results

Preoperative and postoperative K values from the topographic maps were compared, and changes in overall astigmatism ($K_{\max} - K_{\min}$) were calculated. K values in the preoperative eye (in vivo) were 44.03/47.98@84. The K values changed to

44.81/46.74@99, 44.58/47.48@84, and 45.43/46.37@84 with AK, CXL, and AK + CXL, respectively. Corneal astigmatism was reduced from 3.95 diopters (D) in the preoperative state to 1.95D, 2.89D, and 0.94D with AK, CXL, and AK + CXL, respectively. Figure 1 shows the axial curvature topographical maps of preop and postop cornea.

Discussion

Clinically significant reductions in astigmatism were achieved with collagen crosslinking and AK. Under the model assumptions and treatment patterns simulated in this preliminary comparison, the treatment effect was greatest for AK + CXL, followed by AK, and then CXL. CXL is a less-invasive alternative to AK that resulted in a more regular anterior corneal surface. This preliminary work suggests that AK and CXL could be used as complementary procedures to achieve greater effect than achievable with either procedure alone.

References

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