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ORIGINAL ARTICLE

Finite element modeling of circular keratotomy in the normal, astigmatic, and keratoconic cornea

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Abstract

Purpose: The purpose is to evaluate the effect of a circular relaxing incision (circular keratotomy [CK]) on corneal biomechanics using finite element analysis (FEA) of *in silico* models of a spherical cornea, cornea with astigmatism, and cornea with keratoconus.
Methods: Computer-aided design software and published biomechanical models were used to create a theoretical 3D model of a normal and a keratoconic human cornea. Abaqus FEA software was used to evaluate changes caused by circular incisions performed at different depths and diameters, radial and perpendicular to the corneal surface. To evaluate changes in refractive power, the radii of curvature at the central 3 mm of the cornea were calculated using a Python-based code (Supplemental File 1).
Results: Circular incisions caused flattening of the cornea, which increased when the incisions were deeper and closer to the center. Maximal flattening of 2.75D was demonstrated with an incision of 450 μm depth and 6 mm diameter. A similar incision applied to a keratoconic corneal model with normal elastic properties caused flattening of 7.7D, which increased to 12.25D (from 50.25D to 38D) when Young's modulus was decreased to 30% of baseline, changing the elastic properties. In both models, flattening increased when incisions were made radial rather than perpendicular to the corneal surface. In a cornea with regular astigmatism of 7.89D, a similar incision caused flattening of both flat and steep meridians, with a decrease in astigmatism of 1.1D and 1.6D at diameters of 3 mm and 6 mm, respectively.
Conclusion: FEA demonstrated that CK could flatten both regular and ectatic corneas.

Introduction

Arcuate keratotomy, also known as astigmatic keratotomy or arcuate relaxing incision, is a time-honored procedure to treat regular astigmatism in native eyes during cataract surgery or following keratoplasty. A single or double arcuate incision, done manually with a diamond blade or by femtosecond laser, causes flattening of the treated corneal meridian coupled with steepening of the perpendicular meridian.[1]

During the last 40 years, several studies have investigated the utility of circular keratotomy (CK). The procedure consists of a partial-thickness continuous circular incision centered on the visual axis or respective to the limbus performed on corneas with congenital astigmatism or post-keratoplasty astigmatism and corneas with keratoconus. The incision is intended to mechanically isolate the central cornea from its astigmatic surroundings, thereby decreasing corneal asymmetry and irregularity. Arguably, the scar formed following the procedure can further assist in stabilizing the cornea, but this assumption has yet to be validated.[2-5]

Reports show conflicting evidence regarding the effect of CK on the cornea. One study in a rabbit model showed no change in corneal curvature,[6] whereas another, employing two circular trephines with removal of a lamellar ring, demonstrated corneal steepening.[7] *Ex vivo* experiments in human corneas showed a decrease in astigmatism.[8]

Clinically, a case report describing the progression of myopic astigmatism following CK was published as early as 1982.[9] In 2006, Leccisotti[10] discontinued a trial evaluating the effect of CK in patients with keratoconus scheduled for lamellar keratoplasty after two of the first three cases demonstrated progression of ectasia and loss of best corrected visual acuity as soon as 3 months following the procedure. Three years later, Krumeich and Kezirian[2] reported the results of 400 μm deep, 7 mm trephine-assisted CK performed in 46 eyes with Amsler–Krumeich stage I/II keratoconus between 1993 and 2006. Corneal astigmatism was significantly reduced, with stabilization of refraction in 64% of patients at 1 year postoperatively. Best spectacle-corrected visual acuity improved by two lines or more in 43% of patients and was reduced in 9% at the last follow-up. A double-running suture was placed during the first 6 postoperative months. Recently, Hagen *et al.*[11] reported that 9 out of 10 eyes with stage I/II keratoconus that underwent femtosecond-assisted CK remained stable during a 3-year follow-up.

Comparison of these case reports and series is challenging because of the inherent heterogeneity of the studied patients and differences among the described techniques. The aim of the present study was to create an *in silico* model that will make it possible to evaluate this procedure in a controlled biomechanical environment. Finite element analysis (FEA), an effective, extensively applied noninvasive method for analyzing corneal biomechanics,[12] was used to evaluate the effect of CK performed on a spherical cornea, a cornea with regular astigmatism, and a cornea with keratoconus.

Materials and Methods

3D modeling of the human cornea

Idealized anatomy models

Solid works (3DS Corporation, Waltham, MA), a computer-aided design (CAD) software, and a previously published biomechanical model[13] were used to create a theoretical 3D model of an ideal spherical human cornea. Briefly, the sclera was modeled as a 26 mm hemisphere with 1 mm thickness. The cornea was modeled with a uniform thickness of 550 μm and 13 mm diameter.

A theoretical model of a keratoconic cornea was created by assuming that the anterior corneal surface can be defined by a circular arc 13.2 mm in diameter, and the posterior corneal surface, by a circular arc 11.4 mm in diameter. The concentric arcs formed thicknesses of 380 μm and 650 μm at the center of the cornea and the limbus, respectively. The radius of curvature was 6.73 mm, corresponding to 50.25D.

An eye with regular astigmatism was modeled using a cornea with radii of 7 mm and 8 mm corresponding to 48.25D and 42.25D, respectively.

FEA

Abaqus FEA software (Simulia, 3DS Corporation) was used to model the deformations caused by circular relaxing incisions performed at different depths and diameters, radial and perpendicular to the corneal surface. The normal corneal tissue was modeled as hyperelastic and isotropic using Yeoh's material model with C_{10}, C_{20} and C_{30} values of 0.14 MPa, 10.19 MPa, and 424 MPa, respectively, based on previous reports.[14] For the keratoconic cornea, a linear elastic isotropic model was used, with a baseline Young's modulus of 3.8 MPa and Poisson's ratio of 0.49. To simulate keratoconic elastic properties, Young's modulus was first decreased to 50% and then to 30% of its baseline value.

Circular incisions, both radial and perpendicular to the corneal surface, were modeled. Incision depth ranged between 50 μm and 450 μm, and incision diameter ranged between 6 mm and 8 mm. Intraocular pressure of 15 mmHg was applied in all models.[15] Changes in refractive power caused by the incisions were calculated by a Python code.

Results

In the present theoretical model, a circular incision flattened the central cornea, and the flattening increased when the incisions were deeper and closer to the center [Figure 1]. A quantitative comparison of the results is given in Table 1. Briefly, a maximal flattening effect of 2.75D at 3 mm corneal diameter and of 5D at 6 mm corneal diameter was demonstrated with a 450 μm-deep incision 6 mm in diameter.

Flattening of 7.7D occurred when a similar incision was applied to a theoretical model of a cornea with keratoconic geometry but normal elastic properties, from 50.25D to 42.5D. The flattening effect increased to 10.75D (from 50.25D to 39.5D) when the elastic properties were changed by decreasing Young's modulus to 50% of its baseline value, and it further increased to 12.25D (from 50.25D to 38D) when Young's modulus was decreased to 30% of its baseline value.

A circular incision of diameter 6 mm and depth 450 μm applied to a cornea with regular astigmatism of 6D caused flattening of both flat and steep meridians, with a decrease of astigmatism by 1.1D at 3 mm diameter and of 1.6D at 6 mm diameter.

In all models, radial incisions with respect to the corneal surface caused more flattening than perpendicular incisions.

Discussion

The present study demonstrated that CK flattens the normal cornea and flattens, to a greater extent, the keratoconic cornea. These results are in line with the clinical reports of Krumeich and Kezirian[2] and Hagen *et al.*[11] which described a postoperative decrease in corneal curvature.

However, two reports described the progression of keratoconus and myopia following CK in three cases.[9,10] In that context, it is reasonable to presume that performing an incision that weakens the cornea, which is ectatic and weak to begin with, would result in progression of ectasia. However, we did not demonstrate this effect in our simulation. This might be explained by several factors.

First, whereas both Krumeich and Kezirian[2] and Hagen *et al.*[11] reported CK results in patients with Amsler–Krumeich stage I/II keratoconus, Leccisotti[10] investigated patients with

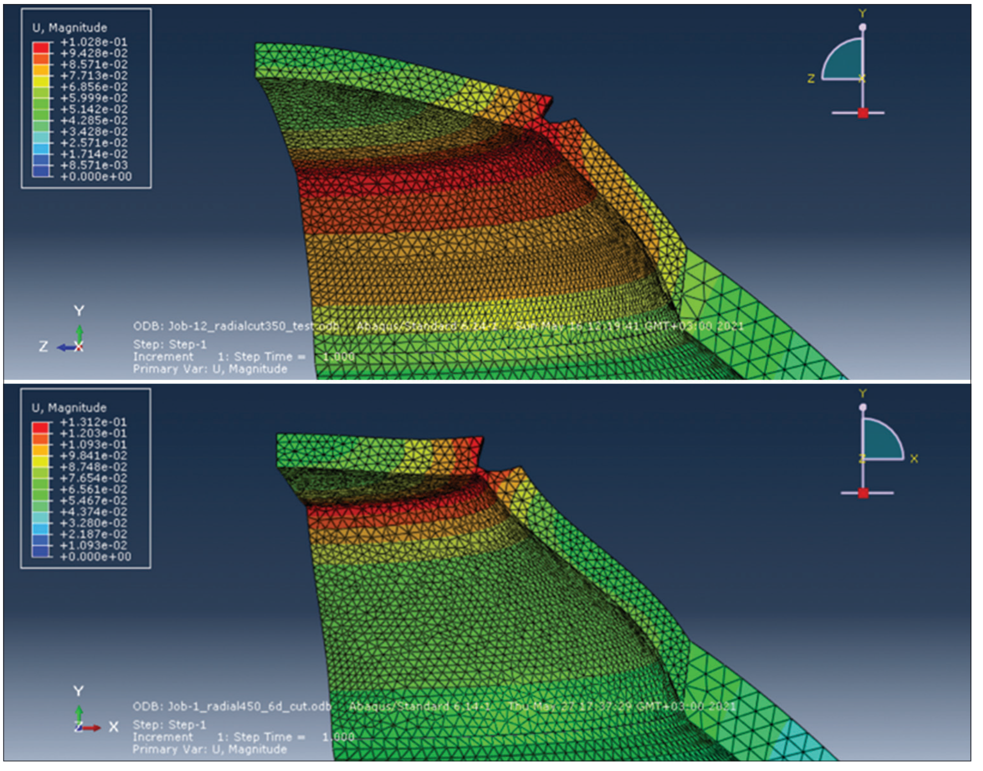

Figure 1: Effect of circular keratotomy on corneal curvature. Finite element analysis of the effect of circular corneal incision on a model of a normal cornea. The flattening effect is increased with increased incision depth. Top panel. Incision measuring 8 mm in diameter made at a depth of 350 µm. Bottom panel. Same incision made at a depth of 450 µm

Table 1: Effect of circular corneal incisions on the central keratometry in a finite element model of a normal cornea

Incision diameter	Incision depth	Change in Keratometry values from baseline	
		At 3 mm diameter (471.5D)	At 6 mm diameter (47.02D)
Incisions made radially to the corneal plane			
8 mm	50 µm	0.033	−0.013
8 mm	100 µm	−0.007	−0.078
8 mm	350 µm	−0.158	−1.144
6 mm	450 µm	−2.748	−5.010
Incisions made perpendicularly to the corneal plane			
8 mm	50 µm	0.046	−0.013
8 mm	100 µm	0.059	−0.059
8 mm	350 µm	0.086	−0.595
6 mm	450 µm	−1.462	−3.312

progressive advanced keratoconus who were scheduled for lamellar keratoplasty. In our study, arbitrary values were used for the geometric and biomechanical material properties of the keratoconic cornea. Perhaps an even more ectatic cornea should have been assumed in order to simulate the progression of ectasia following CK. Using Solid Works CAD software, we recently succeeded in producing a patient-specific geometric model by extracting anterior and posterior elevation coordinates from the Pentacam (Oculus Inc., Arlington, WA) tomography platform and calibrating them using Pentacam thickness maps [Figure 2]. We hope this technique will allow us to simulate the biomechanical response to CK and other interventions in corneas of specific patients.

Second, we did not account for the tissue creep effect (i.e., the gradual elongation and deformation of tissue subjected to steady stress over time) in our simulation. Tissue creep has been suggested as an important contributor to the pathogenesis of keratoconus and iatrogenic ectasia following refractive surgery, and it could be responsible for the progression of ectasia seen in patients following CK.[16]

Third, other biomechanical processes that were shown to occur in keratoconus, such as interlamellar and interfibrillar slippage of collagen within the stroma due to loss of cohesion between collagen fibrils and the non-collagenous matrix, as well as redistribution of stromal mass, might continue or even accelerate following CK in patients with progressive disease.[17] Based on the notion that the sclera of myopic eyes is more elastic than normal sclera,[18] the biomechanical properties of the sclera were also altered in our model. This might have resulted in the expansion of the whole sphere rather than the progression of corneal ectasia.

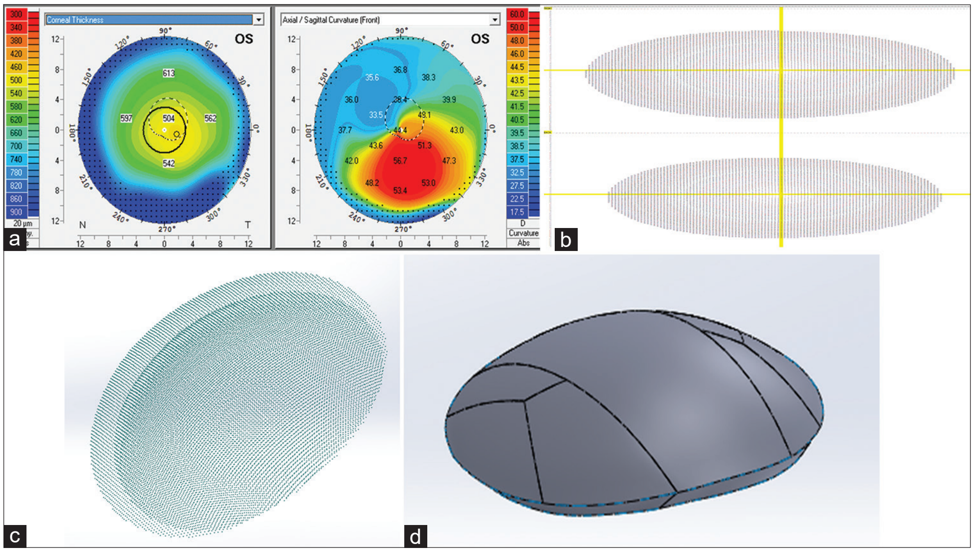

Figure 2: Patient-specific modeling of a keratoconic eye. (a) Pentacam image of a specific patient with keratoconus used to build a model of a keratoconic eye. The anterior curvature as well as the corneal thickness map are shown. (b) Coordinate map of the anterior and posterior surface of the cornea, extracted from the Pentacam tomography software. (c) The same coordinates distributed in a 3D space using SolidWorks software. (d) Final model of the keratoconic eye

Our data showed that CK incisions done radial to the corneal surface caused more flattening than incisions done perpendicular to the corneal surface. This effect probably occurred because radial incisions cross more corneal lamellae than perpendicular incisions due to corneal curvature. It could account for some of the differences shown between the results of manual and femtosecond-assisted keratotomies.[19]

CK had a lesser effect on regular corneal astigmatism than reported for paired arcuate incisions.[18] This was not unexpected given that, unlike arcuate incision, CK not only affects the steep meridians but also weakens the flat ones. However, our model was not able to show whether CK can cause regularization of the complex geometry present in keratoconus, such as displaced cones and proud nebulae.

Conclusion

This study shows that CK causes flattening of the corneal curvature, and this effect is increased in keratoconic corneas. Our model did not demonstrate progression of ectasia following CK, as reported in some patients. Future studies modeling patient-specific geometry and biomechanical properties may allow for mitigation of the risk of ectasia.

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Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

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