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Optical Coherence Tomography to Assess Intrastromal Corneal Ring Segment Depth in Keratoconic Eyes

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Abstract

PURPOSE: To investigate intrastromal corneal ring segment depth with a high-speed corneal optical coherence tomography (OCT) system.

SETTING: Doheny Eye Institute, University of Southern California, Los Angeles, California, USA.

METHODS: A prospective observational case series comprised 4 eyes of 4 patients receiving Intacs intrastromal corneal ring segments (Addition Technology, Inc.) for keratoconus. Optical coherence tomography (OCT) was performed between 7 days and 43 days after implantation.

RESULTS: The slitlamp impression of intrastromal corneal ring segment implantation depth did not correlate well with OCT measurements (r^2 Z 0.68). The fractional implantation depth was correlated with several surgical variables using a stepwise multivariate regression model, and 2 statistically significant correlations were found. The position of the distal portions of the ring segments was shallower than that of the portion closer to the insertion site (P Z .003). Segments placed in the inferior cornea (P Z .008) experienced more distal shallowing. Shallower depth was associated with greater fractional anterior stromal compression (P Z .04).

CONCLUSIONS: Shallower placement of intrastromal corneal ring segments may result in more complications, such as epithelial-stromal breakdown and extrusion, because of the greater anterior stromal tensile strain. The distal and inferior portions of intrastromal corneal ring segments tended to be placed at a shallower depth. Optical coherence tomography provided precise measurement of ring segment depth and may help identify implants that pose a greater risk for depth-related complications.

Keratoconus is a progressive disease that causes thinning and ectasia of the corneal stroma, leading to decreased visual acuity from irregular astigmatism. Traditionally, keratoconic eyes are corrected with spectacles and rigid gaspermeable (RGP) contact lenses when possible. When these conservative measures prove intolerable or unsatisfactory, penetrating keratoplasty (PKP) is considered. Penetrating keratoplasty for keratoconus provides good visual results in most cases,¹ and complication rates have decreased over the past decade.² However, immune rejection and long-term endothelial failure remain significant risks.³ In rare cases, keratoconus may recur 15 to 20 years later in the transplanted cornea.⁴

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An alternative to PKP for the treatment of keratoconus is the use of intrastromal corneal rings. Intrastromal corneal rings were first used to correct low myopia. They act as passive spacing elements in the midperiphery, shortening the arc length of the anterior corneal surface and thereby flattening the central cornea.⁵ Several researchers have implanted intrastromal corneal rings in eyes with keratoconus and reported good visual acuity and keratometric outcomes.⁵⁻⁷ In addition, the ring segments can be safely removed to reverse the refractive effects.^{8,9}

The rate of serious complications caused by intracorneal ring implantation is reported to be between 1.1% and 2%.^{10,11} Shallow segment depth has been associated with several of these complications, including ring superficialization, stromal thinning, and epithelial breakdown.^{3,10-12} More accurate segment depth measurements may help identify factors associated with depth-related complications.

Traditional evaluation of intrastromal corneal ring segment depth depends on slitlamp impression by the surgeon and may not accurately assess segment depth. Optical coherence tomography (OCT) is a cross-sectional, 3-dimensional imaging modality that uses low-coherence interferometry to achieve axial resolutions in the range of 3 to 20 μm .^{13,14} Unlike ultrasound, OCT does not require fluid immersion or probe contact. In addition, a large area of the eye can be imaged with a single scan. Therefore, with a single scan, OCT can capture the ring segment depth at a series of positions with a high degree of accuracy.

The purpose of this study was to assess intrastromal corneal ring segment depth using an investigational corneal and anterior segment OCT (CAS-OCT) system. To our knowledge, no previous studies have used a high-speed OCT system to measure intrastromal corneal ring segment depth.

PATIENTS AND METHODS

This prospective observational case series comprised all patients who received intrastromal corneal ring segments for the management of keratoconus or iatrogenic keratoconus (keratectasia) between November 1, 2004, and August 1, 2005, at the Doheny Eye Institute. All patients were asked to participate if the CAS-OCT system and operator were available at their nominal 1-week or 1-month postoperative visit. The OCT was performed between 7 days and 43 days postoperatively.

Four eyes of 4 patients were enrolled in the study. Patient charts were reviewed for preoperative and postoperative visual acuity and relevant clinical examination findings, including clinical impression of ring segment depth by slitlamp biomicroscopy. Written informed consent was obtained from all patients according to a protocol approved by the Institutional Review Board of the University of Southern California.

Intacs intracorneal ring segments (Addition Technology, Inc.) were inserted according to the manufacturer's recommended technique. The incision was placed on the steep corneal meridian based on the manifest refraction and corneal topography. The channels were created using mechanical dissectors. Symmetric ring segments were inserted in 2 cases, and asymmetric placement was chosen for the other 2 cases.

A high-speed CAS-OCT prototype (Carl Zeiss Meditec, Inc.) was used to measure intrastromal corneal ring segment depth. It delivered 5.0 mW of optical power at the corneal plane and acquired 2000 axial scans (A-scans) per second. The axial resolution was 17 μm , full-width-half-maximum in the cornea. The transverse resolution was 45 μm based on the focused beam diameter. The Zeiss prototype has an internal fixation target with accommodation control. The system provides real-time display of video camera and OCT images of the area under examination.

The OCT imaging was performed using the pachymetry map pattern consisting of 8 evenly spaced meridional lines 10.0 mm in length. Each line consisted of 128 A-scans. The A-scans were 4.0 mm in depth (Figure 1, A). The depth of the corneal ring was measured at 7 positions along each segment (Figure 1, B). The angular position was numbered as $n = 1$ to 7, where 1 was the closest to the incision site and 7 was the farthest. It was also expressed as the angular distance (degrees) away from the incision site.

Three measurements were obtained at each position:

1. A, the depth from the anterior corneal surface to the inner edge (the edge with the shorter radial distance from the corneal center) of the ring segment (Figure 1, C)
2. A', the depth from the anterior corneal surface to the anterior ring surface at the center of the segment along the radial dimension (radially positioned midway between the inner and outer edges) (Figure 1, C)
3. T, the total corneal thickness just central to the inner edge of the ring segment (Figure 1, D).

The following variables were then calculated:

1. True fractional depth: $d = A/T$
2. Apparent fractional depth: $d' = A'/T$
3. Fractional compression: $c = (A - A')/A$, which is the estimated degree of corneal compression anterior to the segment
4. Fractional thinning: $h = T_n/T_2$, where T_2 is total corneal thickness T measured at position 2 and T_n measured at position n; position 1 not used because OCT images sometimes do not capture it
5. Fractional shallowing: $s = d_n - d_2$, where d_2 is fractional thinning f measured at position 2 and d_n measured at position n

The correlation between OCT-measured fractional depth d and d' was evaluated. Linear regression was applied to fractional compression c and segment depth A to determine whether more superficially placed segments lead to more stromal compression. A multivariate regression model was used to find factors associated with greater fractional shallowing s . Three independent variables were tested: the angular position (in degrees), the segment position (nasal-temporal, superior, inferior), and fractional thinning h . Stepwise multivariate analysis was performed to determine which variables were significant independent predictors of fractional shallowing. All calculations were performed with JMP software version 4 (SAS Institute).

RESULTS

Case 1

A 47-year-old man with a history of keratoconus, pseudophakia, and RGP intolerance in the right eye had a best corrected visual acuity (BCVA) of 20/100 in the right eye with a manifest refraction of $-5.75 + 2.75 \times 50$. The right eye had intrastromal corneal ring implantation. Through a superior (90-degree) incision, nasal and temporal 0.35 mm thickness ring segments were placed. Six weeks postoperatively, the BCVA was 20/60 and the manifest refraction was $+0.50 + 0.75 \times 170$. No complications were noted.

Case 2

A 35-year-old woman with keratoconus and RGP intolerance had a BCVA of 20/40 with a manifest refraction of $-4.00 + 3.00 \times 5$ in the left eye. Through a temporal (25-degree) incision, a 0.35 mm superior segment and a 0.25 mm inferior segment were placed. Three weeks postoperatively, the BCVA was 20/30 with $+1.50 + 1.75 \times 165$. No complications were noted.

Case 3

A 64-year-old man with forme fruste keratoconus and RGP intolerance presented to consider alternatives to spectacles. In the right eye, the uncorrected visual acuity (UCVA) was 20/40 and the BCVA was 20/20 with a manifest refraction of $-2.00 + 1.00 \times 180$. The patient had 0.25 mm intrastromal corneal ring segments superiorly and inferiorly through a temporal (175-degree) incision. One week postoperatively, the UCVA in the right eye was 20/25 and the BCVA was 20/20 with a manifest refraction of $+0.75 + 0.75 \times 5$. No complications were noted.

Case 4

A 44-year-old man with a history of laser in situ keratomileusis (LASIK) in both eyes 4 years previously presented for evaluation of progressive decreasing vision bilaterally for 1 year. The BCVA in the right eye was 20/30 with $-3.50 + 5.50 \times 173$. Approximately 10.00 diopters of inferior steepening and irregular astigmatism were noted in both eyes, consistent with keratectasia. Serial examination revealed continued steepening, and the patient had intrastromal corneal ring implantation in the right eye with placement of two 0.35 mm segments superiorly and inferiorly through a temporal 80-degree incision. The postoperative OCT showed a shallowly positioned inferior segment. A detailed line horizontal scan showed the distal portion of the inferior segment was positioned in the LASIK flap interface (Figure 2). One week postoperatively, the UCVA in the right eye was 20/60.

Quantitative Analysis

The visual acuity and refraction in the 4 patients before and after intrastromal corneal ring implantation are shown in Table 1. A ring segment study number (RSSN) was assigned to each implanted segment (Table 2). Table 2 also shows the size and position of each segment. The OCT measurement of the mean segment depth A and A' was plotted against the slitlamp impression of mean segment depth (Figure 3). The r^2 values for the linear regression model for A and A' against slitlamp impression were 0.68 and 0.74, respectively.

Fractional compression of the cornea anterior to the segment c was plotted against the mean segment depth A (Figure 4). Linear regression was performed, and greater fractional compression was associated with a shallower mean segment depth ($P = .04$).

The true fractional depth d of superiorly placed segments (RSSN 4, 6, and 8) was 64%, 64%, and 60%, respectively. The true fractional depth for corresponding inferiorly placed segments (RSSN 3, 5, and 7) was 72%, 67%, and 40%, respectively. There was no significant difference between the fractional depth of superiorly placed segments and inferiorly placed segments.

Stepwise multivariate analysis showed the angular position from the incision site ($P = .003$) and the segment position ($P = .008$) were significantly correlated with the fractional shallowing of a segment. Figure 5 shows the fractional shallowing s plotted in relation to the angular position of the segment and segment placement. The segments appeared to be shallower at positions farther from the incision. The progressive shallowing was absent in the superiorly placed segments, more notable in the inferior halves of nasally and temporally placed segments, and most severe in the inferiorly placed segments.

DISCUSSION

The slitlamp impression of corneal ring segment depth was not simply related to the OCT measurements (Figure 3). The slitlamp estimate appeared to depend on where the observer chose to measure the segment depth. The slitlamp impression was closer to the apparent depth A' in superficially positioned rings (RSSN 1, 2, 7, and 8), where the examiner estimated the corneal depth anterior to the ring segment in the middle of the ring width and compared it with the corneal thickness at the inner edge of the ring segment. For more deeply positioned rings (RSSN 3, 4, 5, and 6), the slitlamp impressions were closer to the true depth, where the examiner estimated the corneal depth anterior to the inner edge of the ring segment and compared it with the full-corneal thickness at the same position. Overall, the slitlamp impression exaggerated the shallowness of shallow segments and the depth of deeply placed segments. Corneal and anterior segment OCT may provide more accurate and objective measurement of ring segment depth.

The distal portion of the ring segments tends to be shallower. This trend was not seen with the segment implanted in the superior cornea; however, it was obvious for the inferior portions of nasal and temporal segments and very pronounced for the segments in the inferior cornea. All patients had inferiorly positioned cones. We hypothesize that the weaker and more flexible inferior cornea may bow downward ahead of the mechanical dissector, causing the channel to progressively shallow during the dissection process. Since the inferior cornea is already thinner in these cases, shallowing is of greater concern.

Based on these results, keratoconic eyes with a very thin inferior cornea may be at greater risk for depth-related complications. The surgeon may have to exercise caution in placing segments in the inferior cornea to treat inferior ectasia in keratoconus, keratectasia, and pellucid marginal degeneration. In addition, the manufacturer may consider modifying the bevel on the leading edge of the dissector to encourage deepening rather than shallowing of the channel during dissection. Femtosecond laser channel dissection at a constant depth may be a better option.

The allocation of ring segment thickness and position has been an area of active discussion. Swanson reported good results with asymmetric ring placement (with a thicker superior ring and a thinner inferior ring) in 38 patients with pellucid marginal degeneration: 70% of their patients experienced 3 or more lines of improvement in visual acuity, and 90% of their patients showed cone displacement centrally (M. Swanson, "Corneal Architecture Remodeling with Intacs for Pellucid Marginal Degeneration," presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery, San Diego, California, USA, May 2004). The authors hypothesize that placing the thicker segment superiorly may exert a pulling force that displaces the cone centrally. Future studies could explore asymmetric placement with a thicker superior segment, or even placement of a single segment superiorly. Good results have also been reported with placement of the thicker segment inferiorly over a mean follow-up of 9 months.⁵ Our results suggest that if only a single segment is to be implanted, superior placement might be safer.

Our study showed a significant correlation between segment depth and anterior stromal compression. This is to be expected because the tension from corneal ring insertion is borne by a thinner layer of anterior stroma, leading to greater tensile stress (force per cross-sectional area). Greater stress leads to more strain, and more transverse strain naturally causes compression in the depth dimension. The left-most point in Figure 4 (RSSN 7, patient 4) was an exception. This ring segment was shallow, but the cornea anterior to it was not compressed. We believe the lack of anterior stromal compression in this case was caused by placement of the channel in the flap space. The flap could easily move to drape over the segment rather than experience localized strain. The detailed OCT image clearly shows the flap being lifted in this

case (Figure 2). This unintended effect may actually have been protected there was no epithelial breakdown at the shallow distal portion of the segment and a stable BCVA of 20/20 - was achieved.

Shallower ring segments may result in more complications, such as epithelial and stromal breakdown and ring extrusion, because the anterior stromal compression is greater. The greater tensile strain on the anterior stroma could lead to gradual stromal breakdown in a process similar to keratoconus disease progression. In addition, these regions may experience more forward bowing of the anterior corneal surface over the implant. The greater anterior surface curvature may explain the epithelial breakdown. Superficially placed segments also may compromise diffusion of nutrients to the epithelium. In vivo confocal microscopy of intrastromal ring segments have shown epithelial cells with highly reflective nuclei in regions over the segment, which may indicate increased biologic stress caused by the device.¹⁶

Imaging of ring segments has been reported using very-high-frequency ultrasound¹⁷ and lower speed retinal OCT systems¹⁸ in patients with low myopia. This study is the first to use a high-speed CAS-OCT system to assess ring segment depth. The high speed allowed us to obtain a quick survey of ring segment depth greater than 360 degrees. The measurement was rapid and noncontact and allowed us to detect the change in channel depth along the insert path.

In conclusion, high-speed CAS-OCT provided precise assessment of intrastromal corneal ring segment depth and may help identify patients at greater risk for depth-related complications. The Visante OCT system (Carl Zeiss Meditec, Inc.) is similar to the prototype used in this study. The Visante, approved by the U.S. Food and Drug Administration in October 2005, may provide a readily available tool for noncontact measurement of ring segment depth after intrastromal corneal ring implantation.

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Figure 1.

Optical coherence tomography corneal ring measurement scheme. *A*: The pachymetry map pattern provides OCT scans along 8 evenly spaced meridians *B*: The numbering system labels the positions at which the OCT scans cross ring segments, using the incision site as the starting reference position. *C*: Depth from the anterior corneal surface to the inner edge of the ring segment (*A*) and depth from the anterior corneal surface to the anterior ring segment surface midway across its width (*A'*). *D*: Total corneal thickness measured at the inner edge of the segment (*T*). *P* is the distance from the posterior corneal surface to the inner edge of the ring segment. $P = T - A$.

Figure 2.

Case 4. Detailed horizontal-line-scan OCT cross-section showing the distal portion of the inferior ring segment in the LASIK flap interface. Fluid spaces adjacent to the segment indicate the flap was lifted off the stromal bed. The line scan was 12.0 mm in length and consisted of 512 A-scans. Four consecutive frames were registered for each line scan and averaged to increase the signal-to-noise ratio.

Figure 3.
Optical coherence tomography fractional depth measurements plotted against slitlamp impression of the depth of intrastromal corneal ring segments.

Figure 4.

Fractional anterior compression plotted against the mean depth of the segment. The highlighted point corresponds to RSSN 7 in Case 4, in which the distal portion of the segment was located in the LASIK flap interface.

Figure 5. Fractional shallowing plotted against the angular position from the incision site. The segments are classified by placement orientation.

Table 1

Preoperative and postoperative visual acuity and refraction.

Pt	Age (Y)	Status	UCVA	BCVA	Manifest Refraction
1	47	Pre-implant Post-implant	20/100 20/40	20/60 20/40	-5.75 + 2.75 × 50 +0.50 + 0.75 × 170
2	35	Pre-implant Post-implant	20/100 20/80	20/40 20/30	-4.00 + 3.00 × 5 +1.50 + 1.75 × 165
3	64	Pre-implant Post-implant	20/40 20/25	20/20 20/20	-2.00 + 1.00 × 180 +0.75 + 0.75 × 5
4	44	Pre-implant Post-implant	20/40 20/60	20/30 20/20 ²	-3.50 + 5.50 × 173 -5.25 + 1.50 × 135

BCVA = best corrected visual acuity; Pt = patient; UCVA = uncorrected visual acuity

Table 2

Intrastromal corneal ring segment size and position. Each segment is designated by a ring segment study number for plotting.

Pt	Ring Segment Location	Ring Thickness (mm)	RSSN
1	Nasal	0.350	1
	Temporal	0.350	2
2	Inferior	0.350	3
	Superior	0.250	4
3	Inferior	0.250	5
	Superior	0.250	6
4	Inferior	0.250	7
	Superior	0.350	8

Pt = patient; RSSN = ring segment study number