Intrastromal Corneal Ring Segment Implantation by Femtosecond Laser for Keratoconus Correction

Mohamed H. Shabayek, MD, MSc,[1,2] Jorge L. Alió, MD, PhD[1]

Purpose: To report the outcomes after the implantation of intrastromal corneal ring segments (KERARING) aided by femtosecond laser for the correction of keratoconus.

Design: Prospective consecutive interventional study.

Participants: Twenty-one eyes of 16 consecutive keratoconic patients with mean age 32±10.2 years. Forty-five percent were keratoconus grade I, 20% grade II, 15% grade III, and 20% grade IV.

Methods: Intrastromal corneal ring segments KERARING were implanted for keratoconus correction after corneal tunnel creation with the aid of femtosecond laser (IntraLase Corp, Irvine CA).

Main Outcome Measures: Uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), refractive outcome, complete ophthalmologic examination, videokeratography, and corneal higher order aberrations (HOA) were determined or performed before and after surgery at 1 day, 1 week, and 3 and 6 months. In addition, operative and postoperative complications were recorded.

Results: KERARING implantation significantly increased UCVA from 0.06 to 0.3 ($P \leq 0.0001$), BSCVA from 0.54 to 0.71 ($P \leq 0.0003$), and decreased the spherical equivalent by 2.28 diopters (D) and the average keratometric values (K value) by 2.24 D ($P < 0.001$). There was no significant difference between the 3 and 6 months follow-up. Forty percent (8 eyes with a relatively low RMS of total HOA) showed a nonsignificant increase in the RMS of total HOA and 60% (12 eyes with a relatively higher RMS of total HOA≥3.0 μm) showed significant ($P \leq 0.01$) decrease in the RMS of total HOA due to a significant ($P \leq 0.003$) reduction in coma and comalike aberrations. The amount of change in corneal curvature (biomechanical response) ranged from a decrease of 18% from its initial value to an increase of 2.75% and was not correlated to any preoperative parameter. Localized infectious keratitis occurred in only 1 eye (4.8%), and incision opacification occurred in 8 eyes (38%).

Conclusion: Intrastromal corneal ring segment implantation with femtosecond laser is an effective method for correcting keratoconus with reduction in corneal HOA in eyes with coma aberration > 3.0 μm. *Ophthalmology 2007;xx:xxx © 2007 by the American Academy of Ophthalmology.*

Keratoconus is noninflammatory progressive corneal thinning of unknown etiology characterized by steepening and paracentral thinning, resulting in irregular astigmatism and progressive myopia and eventually leading to a decrease in visual acuity.[1–3] Keratoconus correction has always been a challenge, however, in the early stages, spectacles or contact lenses can correct keratoconus, whereas in advanced cases with severe corneal irregularity and stromal opacities, corneal grafting, despite its technical, biological and refractive complications may constitute the last surgical alternative.[4]

Various surgical procedures have been investigated for keratoconus correction with a clear cornea and contact lens intolerance including radial keratotomy, photorefractive keratectomy, and phototherapeutic keratectomy, which are considered as weakening procedures. However, these procedures did not gain popularity due to the disappointing results and lack of predictability and stability.[5,6]

Intrastromal corneal ring segments have been recently proposed and investigated as an additive surgical procedure for keratoconus correction, which provides an interesting alternative aiming at delaying if not avoiding corneal grafting in keratoconus patients.[7–11] Intrastromal corneal ring segments act by an "arc-shortening effect" on the corneal lamellae and flatten the central cornea.[12] The main advantages of intracorneal ring segments are safety, reversibility, stability,[10] and the fact that the surgical process does not affect the central corneal visual axis.[10–16]

Currently, 2 types of intrastromal corneal ring segments are available for ophthalmic surgeons. The first is Intacs

Originally received: June 15, 2006.
Accepted: November 4, 2006. Manuscript no. 2006-651.

[1] Vissum Instituto Oftalmológico de Alicante/Department of Cornea and Refractive Surgery and Division of Ophthalmology, Miguel Hernández University Medical School, Alicante, Spain.

[2] Research Institute of Ophthalmology, Giza, Egypt.

Supported in part by a grant from the Spanish Ministry of Health, Instituto Carlos III, Red Temática de Investigación en Oftalmología, Subproyecto de Cirugía Refractiva y Calidad Visual, Madrid, Spain (grant no. C03/13).

The authors have no financial interest in any of the issues mentioned in the article and have no proprietary interest in the development or marketing of regents or materials used in the study.

Correspondence to Jorge L. Alió, MD, PhD, Instituto Oftalmológico de Alicante, Avda. Denia, s/n, VISSUM, 03016 Alicante, Spain. E-mail: jlalio@vissum.com.

Published by Elsevier Inc.
ISSN 0161-6420/07/$–see front matter
doi:10.1016/j.ophtha.2006.11.033

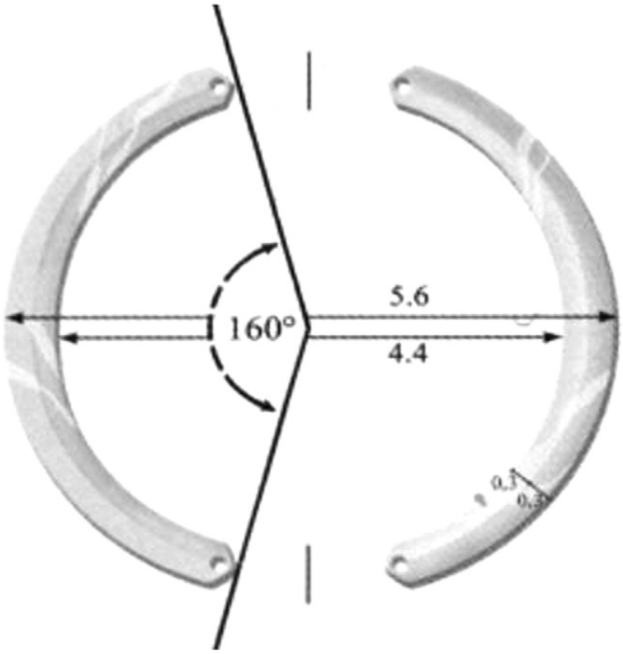


Figure 1. Diagram showing the design and the diameter of intrastromal corneal ring segments.

(Addition Technologies, Fremont, CA) and KERARING, which were originally designed by Pablo Ferrara (Mediphacos, Belo Horizonte, Brazil; Fig 1). Table 1 shows the technical specification of intrastromal ring segments (KERARING). Previous studies evaluated the outcome of Ferrara rings as a potential modality for correcting keratoconus by implanting them more centrally in the corneal stroma (5 mm diameter),[17,18] but reported surgical and postoperative complications.[18]

Recently, femtosecond laser technology (IntraLase Corp, Irvine CA) has been introduced in corneal refractive surgery opening a new frontier and providing a new surgical modality for intrastromal corneal ring segment implantation.[19] In this study, which is the first to our knowledge, we evaluated the visual and refractive outcome as well as the surgical and postoperative complications in addition to changes in corneal higher order aberrations (HOA) after Ferrara rings (KERARING) implantation aided by Femtosecond Laser (IntraLase) for keratoconus correction.

Table 1. Technical Specification of Intrastromal Corneal Ring Segments (KERARING)

Parameter	KERARING
Design (cross-section)	Triangular
Inner diameter	5.40 mm
Outer diameter	6.60 mm
Implantation in respect to	Center of the pupil
Implantation depth	80% of the corneal thickness
Arc Length	120 and 160 degrees
Available segment thickness	0.15, 0.20, 0.25, 0.30, and 0.35 mm
Material	Polymethyl methacrylate or acrylic Perspex CQ

Patients and Methods

Prospective consecutive interventional study including 21 keratoconic eyes of 16 Caucasian patients, 12 males (75%) and 4 females (25%), in whom intrastromal corneal ring segments (KERARING) were implanted with the aid of femtosecond Laser (IntraLase) for keratoconus correction. The mean of the preoperative data is shown in Table 2. We included only eyes with at least 1 keratoconus clinical sign which was confirmed with the videokeratography by a least 100% on the keratometry/inferior–superior asymmetry percent[20] index. Only 1 eye was excluded from the statistical analysis because of lower segment explantation owing to late localized infectious bacterial keratitis 2 months after surgery.

Full ophthalmologic examination, including uncorrected visual acuity (UCVA, in decimals), refraction, best spectacle-corrected visual acuity (BSCVA), slit-lamp biomicroscopy, fundus examination, and videokeratography using the corneal map analysis system (CSO, Florence, Italy) were performed on all eyes before surgery and at 3 and 6 months postoperatively. Three successive, well-focused, properly aligned and centered videokeratographic images were obtained for each eye and the patients were asked to blink between each image capture to ensure the elimination of the eye dryness. At least up to 17 mires of the Placido rings had to be continuous to consider the videokeratography as being good quality and satisfactory to be able calculate the Zernike coefficients for a 6-mm simulated pupil so as to evaluate the effect of KERARING with its 5-mm implantation diameter on corneal aberrations.

Corneal aberrations were obtained from the software provided with the videokeratography system (CSO) after including information about corneal elevation, curvature, power, and position of the pupil with Zernike polynomials up to the seventh order to determine the aberration coefficients. The root mean square (RMS) value of the Zernike coefficients (Z) for spherical aberrations (fourth-order component [Z_4] and the sixth-order component [Z_6]) and for the coma and comalike aberrations (third-order compo-

Table 2. Mean of the Preoperative Data

Preoperative	Mean	Standard Deviation	Range
Age (yrs)	32	10.16	19–56
UCVA	0.06	0.07	0.05–0.4
Sphere	−3.92	3.37	+2.00 to −12.00
Cylinder	−4.83	2.07	−1.00 to −9.00
SE	−6.33	3.71	+0.5 to −15.50
BSCVA	0.54	0.26	0.5–0.9
I-S asymmetry	−8.40	4.01	−2.00 to −15.00
K_{max}	51.81	5.69	45.11–64.39
K_{min}	46.64	5.01	40.00–57.41
$K_{average}$	49.23	5.18	43.42–60.38
RMS SA	1.42	1.34	0.31–6.38
RMS CA	3.12	1.33	1.50–6.13
RMS HOA	3.50	1.75	1.63–8.85

BSCVA = best spectacle corrected visual acuity in decimal; I-S asymmetry = inferior superior asymmetry in diopteric value; $K_{average}$ = average Keratometric value for 3 mm pupil in diopters; K_{max} = maximum Keratometric value for 3 mm pupil in diopters; K_{min} = minimum Keratometric value for 3 mm pupil in diopters; RMA HOA = root mean square value of total higher order aberrations for simulated 6 mm pupil expressed in microns; RMS CA = root mean square value of coma and coma-like aberrations for 6 mm simulated pupil expressed in microns; RMS SA = root mean square value of spherical aberrations for simulated 6 mm pupil expressed in microns; SE = spherical equivalent in diopter; UCVA = uncorrected visual acuity in decimal.

nents [Z_3], fifth-order components [Z_5], and seventh-order components [Z_7]) were calculated for simulated pupil diameter of 6 mm for all eyes. Because of the linear independence of the Zernike terms, the total higher order RMS wavefront error was computed by summing up all components (the total RMS error was the square root of the sum of the squares of the RMS values of all the components except astigmatism).

Informed consent from patients was obtained in accordance with the recommendations of the Declaration of Helsinki and after obtaining the approval of the ethical committee of our institute.

Keratoconus Grading

Keratoconus patients were graded according to the Alió–Shabayek[21] modification of Amsler–Krumeich classification: grade I, 9 eyes (45%); grade II, 4 eyes (20%); grade III, 3 eyes (15%); and grade IV, 4 eyes (20%). The steepest corneal area "keratoconus cone" was situated as follows: inferior 10 eyes (50%), inferior and nasal 2 eyes (10%), inferior and temporal 4 eyes (20%), and central 4 eyes (20%).

Surgical Technique

The surgical decision to implant the intrastromal corneal rings was made according to the nomogram provided by the manufacturer (KERARING Mediphacos Inc., Belo Horizonte, Brazil). Eyes with an ectatic area limited to one half of the corneal surface 1 hemimeridian on the videokeratography were implanted with 1 segment whereas eyes with the ectatic areas exceeding the meridian by at least 1 mm on the videokeratography dividing the corneal surface into two halves, were implanted with 2 segments. Central cones, namely, those with almost equal distribution of the ectatic areas between the 2 corneal hemimeridians, were symmetrically implanted and asymmetrical cones, namely, those with the ectatic area asymmetrically distributed between the 2 corneal hemimeridians, were asymmetrically implanted. To summarize, 1 or 2 segments were made according to the distribution of the ectatic area on the corneal surface, whereas the thickness of the segment was made according to the distribution of the ectatic area as well as the spherical equivalent (SE). Figure 2 shows asymmetrical or symmetrical segment implantation in relation to the distribution of the ectatic area as well as segment thickness selections according to the SE.

All procedures were performed under topical anesthesia. Preoperative medication included propacaine 0.5%, ciprofloxacin 0.3%, and oxybuprocaine CIH 0.2%. After marking the center of the pupil and measuring the corneal thickness by ultrasonic pachymetry at the area of implantation (5 mm diameter), a disposable suction ring was placed and centered with respect to the pupil centre.

The tunnel was performed at 80% of the corneal thickness with the aid of femtosecond laser (IntraLase; femtosecond laser 15 kHz), which is an infrared, neodymium glass femtosecond laser (ultrafast 10^{-15} of second) with a wavelength of 1053 nm. The laser beam of 3 μm diameter (spot size) is optically focused at a specific predetermined intrastromal depth by computer scanners, which give a focus (dissection) range between 90 and 400 microns from the corneal anterior surface. This beam forms cavitations, microbubbles, of carbon dioxide and water vapor by photodisruption, and the interconnecting series of these bubbles forms a dissection plane.

Taking into consideration this 400 μm depth limitation (maximum depth allowed), no eyes in this study required > 400 μm depth of implantation, as the mean depth of implantation was 395 μm (range, 360–400 μm). An inner diameter of 4.8 mm and outer diameter of 5.4 mm was programmed with the laser software giving a tunnel width of 0.6 mm, which is equivalent precisely to the segment width and with an incision length of 1.4 mm performed on the steepest topographic axis. In all eyes, the power used to create the tunnel and the incision was 5 mJ. The procedure lasted approximately 15 seconds.

Five minutes later and after clearance of the gas bubbles, the intracorneal ring segments were implanted easily under full aseptic conditions with a special forceps and the segments were placed in the final position with a Sinskey hook through a dialing hole at both ends of the segment. Implantation was difficult in only 1 eye and a 10/0 nylon suture was needed to close the wound, which was removed after 10 days. This eye was excluded from the statistical analysis due to lower segment explantation after late localized infectious keratitis.

Postoperative treatment included combination of antibiotic (tobramycin, 3 mg/ml) and steroid (dexamethasone, 1 mg/ml) eye drops (Tobradex, Alcon Cusi, Barcelona, Spain) 3 times daily for 2 weeks with tapering of the dose for 2 more weeks, in addition to cyclopentolate hydrochloride (10 mg/ml 3 times daily for 1 day; Cycloplejico, Alcon Cusi).

Statistical Analysis

Statistical analysis was carried out using SPSS version 10 for Windows (SPSS Inc., Chicago, IL). Student's *t* test for paired data was used to compare preoperative and postoperative data. Pearson's test was used to correlate between different variables such as the postoperative BSCVA to the keratoconus grade and K value, and also the amount of change in the corneal curvature to different preoperative variables. Out of the 21 consecutive eyes, 1 eye was excluded from the statistical analysis due to lower segment explantation after late infectious keratitis.

Results

Clinical Outcome

No surgical complications such as anterior chamber perforation occurred; all eyes showed excellent corneal tolerance with no extrusion, migration, or visualization around the incision or the tunnels. In addition, neither corneal ulcers nor stromal necrosis superficial to the segment were observed, most of the eyes included in this study showed subconjunctival hemorrhage due to the suction ring of the IntraLase, which subsided spontaneously and completely after 1 week. Figure 3 shows the clinical outcome on the first postoperative day.

Visual Outcome

Mean UCVA increased from 0.06 to 0.3 (range, 0.5–0.7; $P \leq 0.0001$). The mean BSCVA increased from 0.54 to 0.71 (range, 0.05–1.2; $P \leq 0.0003$). Fourteen eyes (70%) showed increase in the BSCVA after surgery, whereas in only 1 (5%) advanced keratoconus eye (grade IV) the BSCVA decreased by 1 line. Five eyes (25%) showed no change in the BSCVA; 4 of these eyes were grade I with initial preoperative BSCVA ranging from 0.7 to 0.9 and 1 eye was grade IV. Figure 4 shows the percentage of eyes in relation to the number of lines of UCVA and BSCVA gained or lost. A significant correlation with the Pearson's test between the keratoconus grade −0.58 (at the 0.01 level), preoperative average K value −0.77 (at the 0.01 level) and the postoperative BSCVA was observed; that is, the higher the keratoconus grade or the average K value, the lower the postoperative BSCVA achieved after surgery.

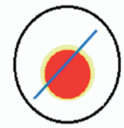
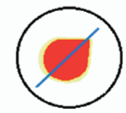
S.E.	0/100	25/75	33/66	50/50
				
	All ectasia is limited to one half of the cornea.	75% of the ectasia in one half of the cornea and 25% situated in the other half.	Two thirds of the ectatic area in one half of the cornea and one third in the other half.	The ectasia is distributed evenly in both corneal halves.
>−10 D	25/35	25/35	30/35	35/35
−8 to −10 D	20/30	20/30	25/30	30/30
−6 to −8 D	15/25	15/25	20/25	25/25
−2 to −6 D	0/20	0/20	15/20	20/20
<−2 D	0/15	0/15	15/15	15/15

Figure 2. Normogram of segment distribution and thickness according to area of ectasia and spherical equivalent (SE). Example: 25/35 = upper segment thickness/lower segment thickness (0.25 mm/0.35 mm). D = diopters.

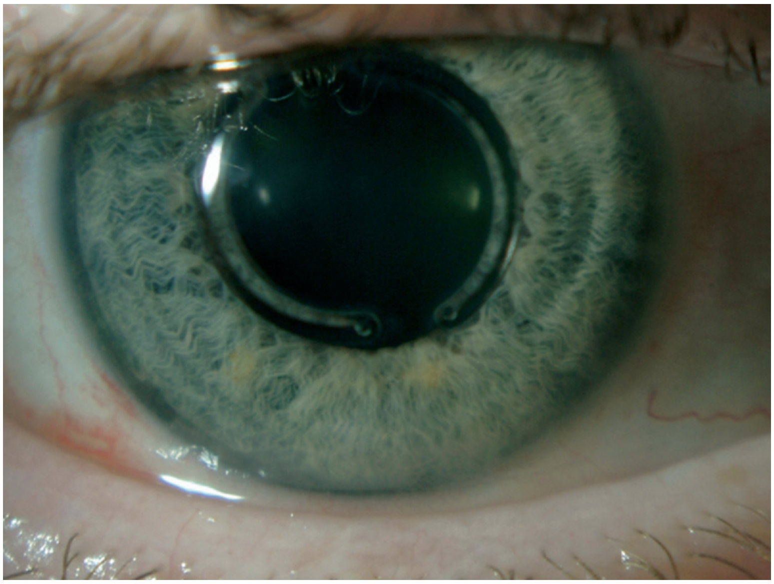


Figure 3. Clinical outcome 1 day postoperative.

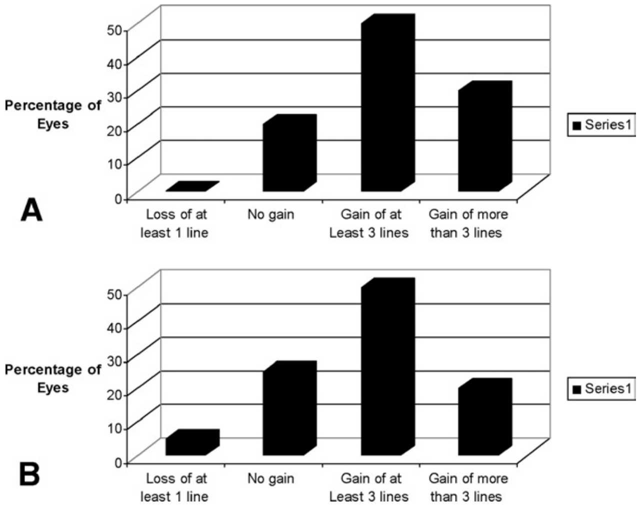


Figure 4. **A**, Percentage of eyes with uncorrected visual acuity (UCVA) gain and loss 6 months after surgery. **B**, Percentage of eyes with best spectacle corrected visual acuity (BSCVA) gain and loss 6 months after surgery.

Refractive Outcome

The mean decrease in spherical power was 0.96 diopters (D; $P \leq 0.04$), in cylindrical power 2.67 D ($P \leq 0.0004$), and in SE 2.23 D ($P \leq 0.0004$).

The topographic K values showed a significant decrease in K_{max}, K_{min}, and $K_{average}$ ($P \leq 0.03$; Table 3). However, when the amount of reduction of the K value or the corneal biomechanical response was calculated by the formula (postoperative $K_{average}$ − preoperative $K_{average}$) × 100/preoperative $K_{average}$, we observed a mean decrease by 4.4%, but ranging from (+2.75% to −17.85%); that is, the change in the corneal curvature in terms of the K value or what we can define as flattening of the corneal curvature (biomechanical response) ranged from an 18% decrease from its initial value to an increase of 2.75%.

Corneal Aberrations

The mean corneal total HOA decreased by 0.53 μm ($P \geq 0.1$). Spherical aberrations (fourth-order component Z_4 and the sixth-order component Z_6) decreased by 0.35 μm and the coma and comalike aberrations (third-order components Z_3, fifth-order components Z_5, and seventh-order components Z_7) by 0.39 μm. When we correlated the amount of decrease in total HOA and initial preoperative HOA, we found a significant correlation of 0.73 at the 0.01 level (Pearson's test), so the higher the preoperative RMS value the higher the amount of reduction we achieved after KERARING implantation.

We divided the eyes into the following groups: eyes with an increase in the HOA RMS value of 40% (8 eyes; 5 eyes grade I and 3 eyes grade II) in which the amount of increase in corneal HOA was not significant and eyes with a decrease of HOA RMS 60% (12 eyes; 7 eyes grade III or IV and 5 eyes grade II) in which the mean reduction in spherical aberrations 0.61 μm ($P \geq 0.1$) was not significant, whereas the coma and comalike mean reduction was 1.01 μm ($P \leq 0.003$) from 3.53μm preoperative to 2.52 μm postoperative and the mean reduction in total HOA was 1.22 μm ($P \leq 0.01$) from 3.99 μm preoperative to 2.77 μm postoperative.

Table 3. Mean of the Keratometric (K) Values before and 6 months Postoperative as Well as the Amount of Reduction

	Preoperative (D)	Postoperative (D)	Pre–Post (D)	*P*
K_{max}	51.34	47.97	3.37	≤0.0002
K_{min}	46.22	45.01	1.21	≤0.03
$K_{average}$	48.79	46.54	2.24	≤0.001

D = diopters; $K_{average}$ = average K value for 3-mm pupil in diopters; K_{max} = maximum K value for 3-mm pupil in diopters; K_{min} = minimum K value for 3-mm pupil in diopters.

Stability

The comparison at 3 and 6 months to evaluate stability showed no significant difference in any parameter; only the mean BSCVA increased from 0.70 at 3 months to 0.76 at 6 months ($P \leq 0.02$). The mean postoperative data at 3 and 6 months are shown in Table 4.

Complications

Difficult implantation was observed in only 1 eye and suture was needed for wound closure. In the same eye, late localized infectious keratitis occurred 1 month after surgery (Fig 5A) with uncorrectable visual acuity of 0.05. Intensive fortified antibiotic and corticosteroid combination (vancomycin, 50 mg/ml; ofloxacin, 5 mg/ml; and dexamethasone, 1 mg/ml) were prescribed every 2 hours for 3 days with a good response after 48 hours. Corneal clarity was achieved 1 week after treatment (Fig 5B) and the fortified antibiotics were stopped with continuation of (tobramycin, 3 mg/ml) and steroid (dexamethasone, 1 mg/ml) eye drops (Tobradex, Alcon Cusi) 5 times daily for 2 weeks with complete visual recovery.

Traces of small localized infectious pockets existed around the lower segment end (Fig 5B), and also owing to tapering the medications, exacerbation of the infection recurred (Fig 5C); 1

Table 4. Mean Postoperative Data

Mean	3 Months	6 Months	*P* Value
UCVA	0.28	0.30	0.2
Sphere	−3.25	−2.88	0.1
Cylinder	−2.15	−2.15	1.0
SE	−4.30	−3.96	0.1
BSCVA	0.7	0.76	0.02
I-S asymmetry	−5.63	−6.07	0.7
K_{max}	48.46	47.97	0.1
K_{min}	45.44	45.01	0.1
$K_{average}$	46.91	46.54	0.2
RMS SA	1.11	0.98	0.1
RMS CA	2.52	2.35	0.07
RMS HOA	2.81	2.60	0.08

BSCVA = best spectacle-corrected visual acuity in decimal; I-S asymmetry = inferior–superior asymmetry in diopteric value; $K_{average}$ = Average keratometric value for 3 mm-pupil in diopters; K_{max} = maximum keratometric value for 3 mm-pupil in diopters; K_{min} = minimum keratometric value for 3 mm-pupil in diopters; RMS CA = root mean square value of coma and comalike aberrations for 6-mm simulated pupil expressed in microns; RMS HOA = root mean square value of total higher order aberrations for simulated 6-mm pupil expressed in microns; RMS SA = root mean square value of spherical aberrations for simulated 6-mm pupil expressed in microns; SE = spherical equivalent in diopter; UCVA = uncorrected visual acuity in decimal.

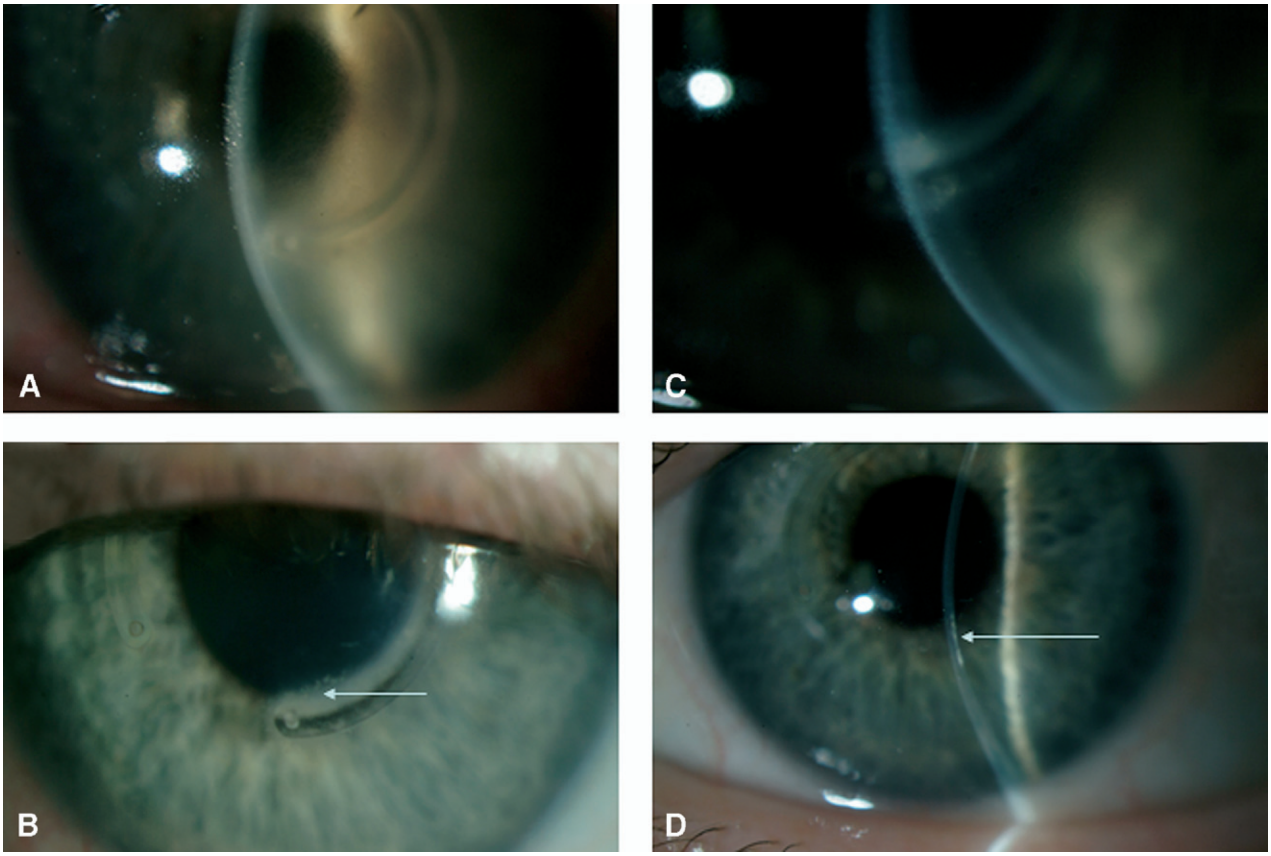


Figure 5. **A**, Localized infectious bacterial keratitis around the lower segment 1 month after surgery. **B**, One week after treatment, there is corneal clarity with small pockets of infection (arrow). **C**, Exacerbation of the infection after withdrawal of steroids. **D**, One month after explantation of the lower segment. The arrow indicates the area of corneal scarring opacity corresponding to the previous segment site.

month later (2 months after the surgery) the segment was explanted by dissecting the incision with a 21-gauge blade and explanting the segment with Sinskey hook and the implantation forceps, followed by tunnel irrigation with buffered saline solution and vancomycin. Despite the negative culture and sensitivity results of the explanted segment, electron microscopy pictures showed debris and necrotic tissue around the segment. One month after the explantation of the lower segment, corneal clarity was recovered but with minimal scarring "stromal opacification," which coincided with the site of the localized keratitis (Fig 5D) and the BSCVA was restored to the initial preoperative level but with an increase in the SE by 11.25 D when compared with preexplantation data of the lower segment. The refractive data of this eye are shown in Table 5.

In 8 out of 21 eyes (38%), superficial corneal opacification coinciding with the incision site occurred (Fig 6) No further complications such as extrusion, decentration (migration), disciform keratitis or corneal vascularization were observed as previously reported.[18]

Discussion

Implantation of the intrastromal corneal ring segment (KERARING) more centrally at a 5 mm diameter theoretically will achieve a greater flattening of the central cornea and lead to more efficient correction of keratoconus. According to Patel et al,[22] who studied different mathematical models to predict the effect of intracorneal ring segments for myopia correction in relation to corneal asphericity and the spherical aberration of the eye, the larger the diameter (9 mm) and the thinner the ring (0.1 mm), the less likely they are to adversely affect corneal asphericity "flatten the cornea" and therefore not enhance induction of spherical aberration. In addition, they concluded that an intracorneal ring could not correct more than −4 D of myopia without significantly increasing the spherical aberration, which, in turn, will affect the final visual outcome. In a simplified way and considering that the keratoconic cornea is more elastic than a myopic cornea, which leads to a greater flattening effect after intrastromal corneal ring segment implantation, we can conclude that, to achieve a greater flattening effect and therefore more effective correction for keratoconus, we need either to implant a thicker segment or to implant the segment more centrally, which might induce HOA, especially spherical aberrations, taking into consideration that the keratoconic eye is a highly aberrant eye with significantly higher values of coma and comalike aberrations compared to a normal [21] or even to myopic eyes.[23]

As shown from the results, KERARING is an efficient method for keratoconus correction, significantly decreasing

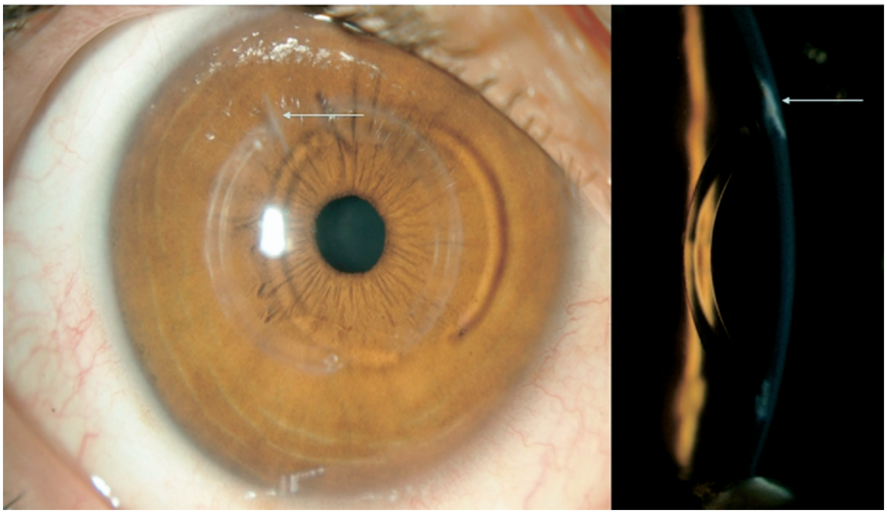


Figure 6. Superficial corneal opacification coinciding with the incision site 1 week after surgery.

the SE by decreasing both the spherical and cylindrical components. It significantly decreases the keratometric values (K_{max}, K_{min}, and $K_{average}$) and significantly increases both the UCVA and BSCVA as well as improving the corneal topography (Fig 7). When comparing our results with previous reports[17,18] that studied Ferrara symmetrical implantation rings for keratoconus correction, our results regarding the increase in the UCVA and BSCVA showed greater improvement, which can be explained by our asymmetrical implantation. We believe that when dealing with an irregular "asymmetrical" corneal surface, asymmetrical implantation provides better results by unequal flattening of the 2 opposite hemimeridians as previously reported.[8–10,13,16] Also, Kwitko and Severo[18] reported that the "central keratoconus group" or keratoconus with central cones had significantly better results after symmetrical implantation, which coincides with the nomogram used in this study. Furthermore, when comparing our results regarding the change in the corneal curvature with those of Kwitko and Severo,[18] they were similar regarding the mean reduction of the $K_{average}$ value. However, when we further analyzed this amount of reduction in relation to the initial preoperative values we observed a change ranging from an increase of 2.75% to a decrease of almost 18%. This variable effect of intrastromal corneal ring segments on corneal curvature was not correlated to any preoperative variable.

Regarding the clinical postoperative complications, we did not observe complications such as decentration or extrusion as reported by Kwitko and Severo,[18] mostly due to the femtosecond technique, which provides a precise depth of implantation all through the tunnel "Planner tunnel," in addition to precise tunnel dimensions, width, and diameter, although 1 eye "excluded from the statistical analysis" showed late localized infectious keratitis around the lower segment which lead to lower segment explanation. The visual acuity (uncorrected and best corrected) was restored to the initial preoperative levels, but with an increase in the SE, which coincides with our previous report although with a different segment type (Intacs),[9] which we believe is due to the unopposed flattening effect of the upper segment. In this study, we report superficial corneal opacification in 8 eyes coinciding with the incision site, which did not affect the visual outcome. This is most probably due to the high energy used for the incision (5 mJ), especially on superficial corneal lamellae. We think that either a faster femtosecond laser (30 kHz) that utilizes lower energy or automatically lowering the amount of energy as the laser

Table 5. Refractive Data of One Eye with Late Localized Infectious Bacterial Keratitis

	Preoperative	Preinfection	Postinfection	Postexplantation
UCVA	<0.05	0.5	0.05	0.05
Sphere	−7.25 D	+0.00 D	+0.00	−11.00 D
Cylinder	−1.25 D	−1.50 D	−1.50 D	−2.00 D
SE	−8.00 D	−0.75 D	−0.75 D	−12.00 D
BSCVA	0.4	0.7	0.05	0.5
K_{max}	51.60 D	45.21 D	—	51.68 D
K_{min}	44.84 D	45.94 D	—	48.05 D
$K_{average}$	48.16 D	45.58 D	—	48.73 D

BSCVA = best spectacle-corrected visual acuity in decimal; $K_{average}$ = average keratometric value for 3-mm pupil in diopters; K_{max} = maximum keratometric value for 3-mm pupil in diopters; K_{min} = minimum keratometric value for 3-mm pupil in diopters; SE = spherical equivalent in diopters; UCVA = uncorrected visual acuity in decimal.

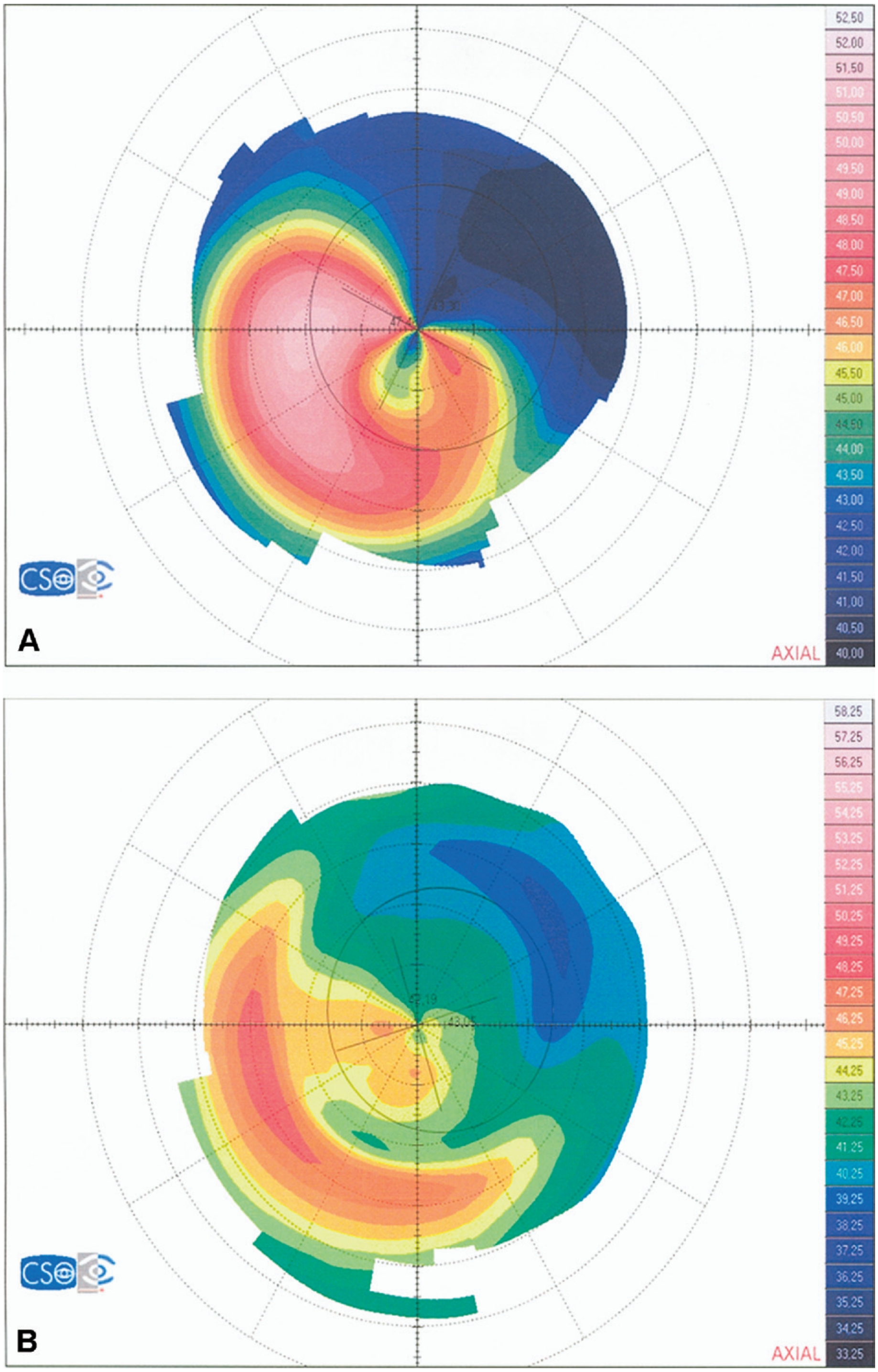


Figure 7. Preoperative (**A**) and 6 months postoperative (**B**) corneal topography.

focus rises to the superficial cornea can eliminate this complication. Table 6 compares the clinical complications with previous reports.

In this study, which we believe is the first to report the results after KERARING implantation with femtosecond laser, no eyes showed a decrease in the UCVA even if we consider the eye that was complicated with localized infectious keratitis. Only 1 eye grade IV (advanced keratoconic eye) lost 1 line of BSCVA, which coincides with previous reports that studied a different type of intrastromal corneal ring segments (Intacs) and concluded that advanced keratoconic eyes[8] or eyes with initial high SE[8,15] showed a decrease in the BSCVA. However, 5 eyes showed a decrease in the SE and K values, an increase in the UCVA, and no increase in the BSCVA due to the high preoperative BSCVA ranging from 0.7 to 0.9 in 4 of these eyes, which

Table 6. Clinical Complications with the Femtosecond Laser and Manual Dissections

	This Study	Kwitko and Severo[18]	Boxer Wachler et al[15]	Alio et al[10]	Alio et al[13]	Colin[24]
Eyes (n)	21	51	74	20	26	57
Type of segment	Ferrara	Ferrara	Intacs	Intacs	Intacs	Intacs
Operative anterior perforation	0	0	1	0	0	0
Deposits	0	X	2	3	Common*	Common*
Extrusion	0	10		7	0	0
decenteration	0	2	1	0	0	0
Keratitis	1	2	0	0	0	0
Vascularization	0	0	0	2	3	0

X = did not comment on deposits.
*Did not comment on the exact number but commented that the complication was common.

were grade I. Only one eye (grade IV) showed an increase in the UCVA with no change in the BSCVA.

When we studied factors that can predict good visual outcome by correlating the postoperative BSCVA with preoperative average K value and the keratoconus grade, as in our previous report,[8] we observed a negative significant correlation by the Pearson's test; that is, the higher the keratoconus grade and the preoperative value, the lower the BSCVA achieved after surgery.

As for corneal aberrations, we preferred to analyze the Zernike polynomials for a 6-mm pupil for 2 reasons. First, it is known that the greater the pupil diameter analyzed, the greater RMS of HOA. Second, we evaluated the aberrations induced for a 6-mm simulated pupil after implanting the segments at the 5 mm diameter. The results showed no induction of HOA (spherical and coma). Contrary to what we expected, the corneal HOA showed a nonsignificant reduction. When we further analyzed the data, we observed that corneal higher aberrations showed a non significant increase in 8 eyes (40%) with relatively low initial corneal HOA (grades I and II or eyes with initial RMS$\leq$3.0 μm). This increase was mainly due to the increase in the spherical aberrations. Although total corneal HOA significantly decreased in 12 eyes (60%) with initially high RMS values of corneal total HOA (grades II, III, and IV or eyes with initial RMS$\geq$3.0 μm). This reduction of total HOA was mainly due to the significant reduction of the coma and comalike aberrations ($P\leq0.003$), whereas the spherical aberrations showed a nonsignificant reduction. This is explained by the amount of spherical aberrations induced by corneal flattening or the formation of a prolate anterior corneal surface after implanting KERARING, which is compensated by the decrease in the coma aberrations after forming a more regular corneal surface. In addition, when treating highly aberrant eyes such as keratoconic eyes (especially grades III and IV), the amount of induced spherical aberrations after surgery is of no significance in relation to the amount of initial or preoperative spherical aberration. In the future, this can serve to help keratoconus patient selection. Patients with preoperative high values of corneal total HOA ($\geq$ 3.03 or keratoconus grade II–IV) are more likely to benefit from KERARING implantation by decreasing total HOA in addition to the visual gain and the good refractive outcome. We could not compare our results with previous authors; to our knowledge, this is the first time corneal aberrations have been investigated after implanting this type of intrastromal corneal rings for keratoconus correction.

When we evaluated the biomechanical corneal response by studying the percentage of change in the corneal curvature after KERARING implantation, the results showed a wide range, from an increase of 2.75% to a decrease of 17.85%. This was not correlated to any preoperative variable and leads to an important question; why is it so variable? Why does the corneal curvature decrease after intrastromal corneal ring segment implantation by 5% and sometimes 10%, and in other patients it even increases by 2%? We think that further studies taking corneal biomechanical properties such as the corneal resistance factor and corneal hysteresis into consideration may provide an answer to this question. We think that this different corneal biomechanical response is due to corneal elasticity; the more elastic the corneal tissue, the greater the ability of intrastromal corneal ring segments to flatten the corneal curvature and correct keratoconus. The corneal resistance factor, corneal hysteresis, and in vivo measurement of the corneal water content may predict the amount of corneal flattening and the outcome of intracorneal ring segments in such an individual pathology as keratoconus.

Despite the limited number of cases in this study, intrastromal corneal ring segments KERARING are an effective and safe method for keratoconus correction and significantly decrease the corneal HOA in eyes with preoperative coma aberrations of >3.0μm (grade II or greater) but with an unpredictable corneal biomechanical response. Femtosecond laser seems to be a better surgical modality for intrastromal corneal ring segment implantation and reduces the risk of operative and postoperative complications. However, further studies are needed to compare and clarify the differences between manual traditional dissection and femtosecond laser dissection. Also further studies with a longer follow-up period and a larger number of patients are recommended to establish the safety of intracorneal ring segments (KERARING) and their role in controlling the progression of keratoconus, given that at least 100 eyes are necessary to detect severe adverse events rates of 3%.[25]

References

1. Rabinowitz YS. Keratoconus. Surv Ophthalmol 1998;42: 297–319.
2. Krachmer JH, Feder RS, Belin MW. Keratoconus and related noninflammatory corneal thinning disorders. Surv Ophthalmol 1984;28:293 322.
3. Tomidokoro A, Oshika T, Amano S, et al. Changes in anterior and posterior corneal curvatures in keratoconus. Ophthalmology 2000;107:1328–32.
4. Barraquer RI. Penetrating keratoplasty in keratoconus. In: Alió JL, Belda JS, eds. Treating Irregular Astigmatism and Keratoconus. El Dorado, Panama: Highlights of Ophthalmology International; 2004:305–33.
5. Doyle SJ, Hynes E, Naroo S, Shah S. PRK in patients with keratoconic topography picture: the concept of a physiological "displaced apex syndrome." Br J Ophthalmol 1996;80:25–8.
6. Kremer I, Shochot Y, Kaplan A, Blumenthal M. Three year results of photoastigmatic refractive keratectomy for mild and atypical keratoconus. J Cataract Refract Surg 1998;24: 1581–8.
7. Colin J, Cochener B, Savary G, Malet F. Correcting keratoconus with intracorneal rings. J Cataract Refract Surg 2000; 26:1117–22.
8. Alió JL, Shabayek MH, Belda JI, et al. Analysis of results related to good and bad outcomes of INTACS implantation for keratoconus correction. J Cataract Refract Surg 2006;32:756–61.
9. Alió JL, Shabayek MH. Intracorneal asymmetrical rings for keratoconus: where should the thicker segment be implanted? J Refract Surg 2006;22:307–9.
10. Alió JL, Shabayek MH, Artola A. Intracorneal ring segments for keratoconus correction: long-term follow-up. J Cataract Refract Surg 2006;32;978–85.
11. Burris TE, Ayer CT, Evensen DA, Davenport JM. Effects of intrastromal corneal ring size and thickness on corneal flattening in human eyes. Refract Corneal Surg 1991;7:46–50.
12. Alió JL, Artola A, Ruiz-Moreno JM, et al. Changes in keratoconic corneas after intracorneal ring segment explantation and reimplantation. Ophthalmology 2004;111:747–51.
13. Alió AJ, Artola A, Hassanein A, et al. One or 2 INTACS segments for the correction of keratoconus. J Cataract Refract Surg 2005;31:943–53.
14. Tunc Z, Deveci N, Sener B, Bahcecioglu H. Corneal ring segments (INTACS) for the treatment of asymmetrical astigmatism of the keratoconus: follow-up after 2 years [in French]. J Fr Ophtalmol 2003;26:824–30.
15. Boxer Wachler BS, Christie JP, Chandra NS, et al. INTACS for keratoconus. Ophthalmology 2003;110:1031–40.
16. Colin J, Cochener B, Savary G, et al. INTACS inserts for treating keratoconus: one-year results. Ophthalmology 2001; 108:1409–14.
17. Siganos D, Ferrara P, Chatzinikolas K, et al. Ferrara intrastromal corneal rings for the correction of keratoconus. J Cataract Refract Surg 2002;28:1947–51.
18. Kwitko S, Severo NS. Ferrara intracorneal ring segments for keratoconus. J Cataract Refract Surg 2004;30:812–20.
19. Ratkay-Traub I, Ferincz IE, Juhasz T, et al. First clinical results with the femtosecond neodynium-glass laser in refractive surgery. J Refract Surg 2003;19:94–103.
20. Rabinowitz Y. Definition, etiology, and diagnosis of keratoconus. In: Alió JL, Belda JS, eds. Treating Irregular Astigmatism and Keratoconus. El Dorado, Panama: Highlights of Ophthalmology International; 2004:241–60.
21. Alió JL, Shabayek MH. Corneal higher order aberrations: a method to grade keratoconus. J Refract Surg 2006;22:539–45.
22. Patel S, Marshall J, Fitzke FW III. Model for deriving the optical performance of the myopic eye corrected with an intracorneal ring. J Refract Surg 1995;11:248–52.
23. Maeda N, Fujikado T, Kuroda T, et al. Wavefront aberrations measured with Hartmann-Shack sensor in patients with keratoconus. Ophthalmology 2002;109:1996–2003.
24. Colin J. European clinical evaluation: use of INTACS for the treatment of keratoconus. J Cataract Refract Surg 2006;32: 747–55.
25. Schachat AP, Chambers WA, Liesegang TJ, Albert DA. Safe and effective. Ophthalmology 2003;110:2073–4.