Customized photoastigmatic refractive keratectomy using combined topographic and refractive data for myopia and astigmatism in eyes with forme fruste and mild keratoconus

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PURPOSE: To examine the outcomes of photoastigmatic refractive keratectomy using corneal and refractive parameters for myopia and astigmatism in eyes with forme fruste and mild keratoconus.

SETTING: Private practice, Melbourne, Australia.

METHODS: Photoastigmatic refractive keratectomy was performed with a Star 1 or Star 2 laser (Visx) in 45 eyes with forme fruste or mild keratoconus using the Alpins vector planning technique. Inclusion requirements were best corrected visual acuity (BCVA) 20/40 or better, no slitlamp signs of keratoconus, mean keratometry less than 50.00 diopters (D), and corneal and refractive stability for at least 2 years.

RESULTS: Thirty-two eyes had follow-up of 5 years and 9 eyes, of 10 years. Preoperatively, the mean refractive astigmatism was −1.39 DC ± 1.08 (SD) (range 0.45 to −5.04 DC) and the mean corneal astigmatism was 1.52 ± 1.18 D (range 0.35 to 4.75 D) by manual keratometry and 1.70 ± 1.42 D (range 0.32 to 5.32 D) by topography. Twelve months postoperatively, the mean refractive astigmatism was −0.43 ± 0.40 D and the mean corneal astigmatism was 1.05 ± 0.85 D by keratometry and 1.02 ± 0.83 D by topography. At 12 months, the uncorrected visual acuity was 20/20 or better in 56% of eyes and 20/40 or better in all eyes. The BCVA was 20/20 or better in 89% of eyes and 20/30 or better in all eyes. Seven eyes had a loss of BCVA, and 16 eyes had a gain. There were no cases of keratoconus progression.

CONCLUSIONS: Photoastigmatic refractive keratectomy in eyes with forme fruste and mild keratoconus was safe and effective for myopia and astigmatism in carefully selected patients with refractive and corneal stability. The incorporation of the corneal astigmatism data into the applied treatment parameters may improve visual and total astigmatism results.

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Keratoconus is a noninflammatory corneal ectasia that, if progressive, is associated with increasing irregular (asymmetrical and nonorthogonal) corneal astigmatism. The condition presents bilaterally, with 1 eye usually affected more than the other. Keratoconus generally first appears in the late teens and early 20s and is usually stable beyond the age of 30 years.[1] It is important to consider a differential diagnosis as several conditions can topographically mimic keratoconus; these include contact lens wear, corneal trauma, and pellucid marginal degeneration (PMD).

Keratoconus can be classified according to severity: forme fruste, mild, severe, and advanced. This classification can be determined by corneal signs on slitlamp examination, keratometry, topography, and corneal steepness.

Amsler[2] first described forme fruste and mild keratoconus in 1937. The signs in these 2 forms are subtle, with no reduction in best corrected visual acuity (BCVA). There is usually no evidence on slitlamp examination, and in most cases the condition at these levels can only be detected using videokeratography. With severe and advanced forms of the disease, slitlamp signs such as Vogt's striae, Fleischer's ring, corneal scarring, and apical thinning are apparent and often associated with a reduction in BCVA proportional to the severity. In many cases, hard contact lens wear can improve BCVA.

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Advances in videokeratography have enabled early detection of subclinical keratoconus. This valuable tool assists surgeons in recommending excimer laser keratorefractive surgery, allowing them to wait until refractive stability and corneal stability are further documented, or in advising against excimer laser surgery. Qualitative patterns of inferior corneal steepening or asymmetric bow tie (Figure 1), together with quantitative keratoconic indices, can be used to gauge the level and progression of keratoconus over time. These indices include the following: (1) Rabinowitz/McDonnell inferior–superior (I–S) value,[3] which quantifies I–S dioptric asymmetry; (2) Smolek/Klyce index,[4] which differentiates keratoconus patterns from astigmatism, PMD, or contact lens warpage; (3) KI–SIA%,[5] which is the product of 4 indices (K-value, I–S value, astigmatism index, and skewed radial axis index), each of which quantifies a topographic feature of keratoconus; (4) corneal irregularity measurement (CIM) (Humphrey Atlas, Zeiss Meditec), which represents the irregularity of the corneal surface; (5) surface asymmetry index (Tomey TMS-2, Computed Anatomy Inc.); (6) Klyce/Maeda keratoconus index[6]; (7) keratoconus prediction index,[6] which determines whether a keratoconus-like pattern is seen in a particular map and quantifies the severity of keratoconus; (8) Fourier analysis of the topographic data, which was recently described as providing additional information on corneal irregularity and progression of the keratoconus[7] (J.L. Alió, MD, PhD, et al., "Fourier Analysis for Normal, Keratoconus and Keratoconus Suspect Eyes," presented at the annual meeting of the American Academy of Ophthalmology, Chicago, Illinois, USA, October 2005).

In the past, refractive excimer laser surgery in patients with keratoconus has generally been approached with some hesitancy. Much of the uncertainty stems from adverse visual outcomes and complications induced with incisional surgery as well as the uncertainty of the natural progression of this ectatic disease.[8,9] A recently published article[10] reporting the onset of ectasia in a 22-year-old who had not demonstrated corneal topographic stability is not convincing evidence that photorefractive keratectomy (PRK) is unsafe in properly selected patients.

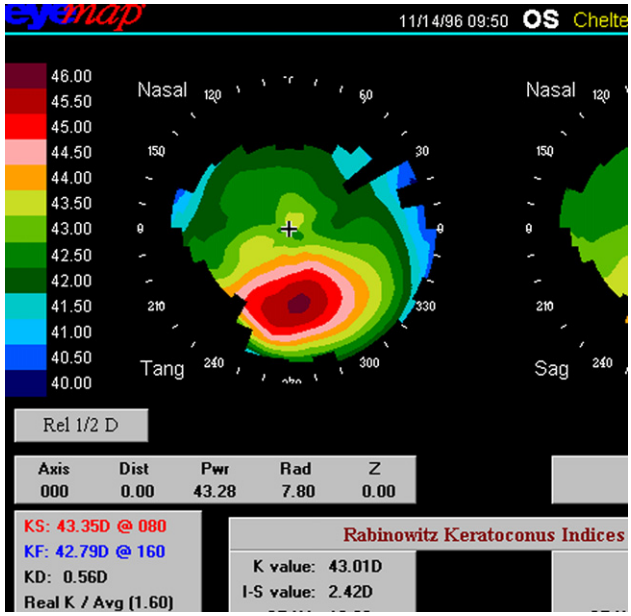

Figure 1. EyeMap showing typical keratoconic profile used in the study with Rabinowitz I–S value.

Several authors[11–15] comment on the safety of photoastigmatic refractive keratectomy (PARK) in eyes with mild and forme fruste keratoconus; however, their studies lacked significant treatment cohorts over an extended period of time. The treatment paradigms for mild and forme fruste keratoconus using PARK in these studies included decentered ablations over the cone,[11] treatments based entirely on corneal parameters such as computer-assisted videokeratography,[12] and most commonly, ablations centered on the pupil dependent exclusively on manifest refraction.[14,15] The visual outcomes in these studies show only a partial decrease in refractive astigmatism and in some cases a progression of keratoconus.[12,13,15] In studies in which the corneal astigmatism was reported postoperatively,[12] a significant amount of astigmatism remained on the cornea that had an adverse impact on uncorrected visual acuity (UCVA) results.

To our knowledge, there are no published reports of using both manifest refraction data and topography or keratometry data in a systematic treatment plan for keratoconus patients having PARK. Because of the irregular shape of the cornea in these patients, larger differences occur between refractive and corneal astigmatism values than would be expected in normal

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eyes (D. Burger et al., "Keratoconus: Diagnosis and Management," Pacific University College of Optometry 2003 [online]. Available at: www.opt.pacificu.edu/ce/catalog/web013/course.htm. Accessed December 16, 2006). This is known as ocular residual astigmatism (ORA)[16,17] and can be quantified by calculating the vectorial difference between refractive and corneal astigmatism (Figure 2). The ORA is also known as intraocular,[18] lenticular,[19] and noncorneal astigmatism.[20]

There is a direct proportional relationship between increasing ORA and topographic disparity,[21] which is a vectorial value for magnitude and axis calculating the separation between the 2 opposite semimeridian astigmatic values. This relationship was shown to be statistically significant in a group of 100 healthy astigmatic corneas before surgery.[21] It is therefore of crucial importance when treating keratoconus that the topography values for astigmatism be incorporated into the treatment plan as treatment based on the manifest refraction or wavefront aberrometry cylinder alone leaves the cornea with excess avoidable astigmatism.[17]

In this retrospective study, we report the results in 45 eyes with mild or forme fruste keratoconus treated with PARK for myopia and astigmatism with long-term follow-up (range 1 to 10 years). Vector planning[16,17] was used in every case to enable treatment parameters to combine topographic and refractive data in a systematic paradigm.

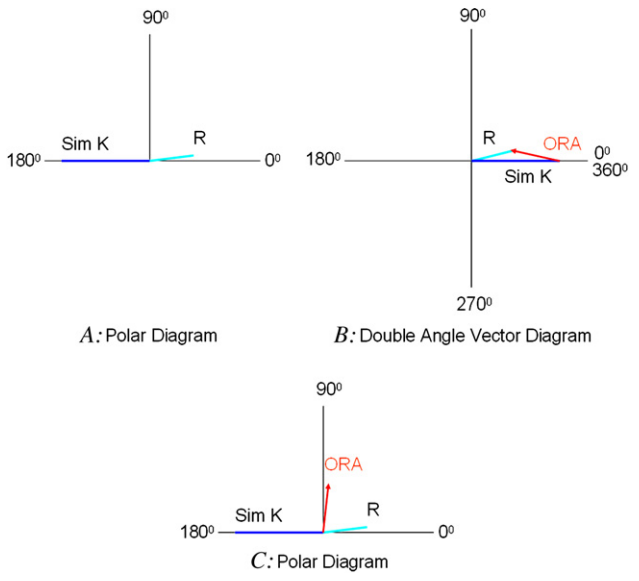

Figure 2. Calculating ORA. *A*: Polar diagram of refractive cylinder at the positive axis and simulated keratometry. *B*: The DAVD showing a "doubling" of the angles without a change in the astigmatic magnitudes. C: Polar diagram displaying the ORA as it would appear on the eye (ORA = ocular residual astigmatism; R = refractive astigmatism (corneal plane); Sim K = simulated keratometry).

PATIENTS AND METHODS

Forty-five eyes of 29 patients with stable, mild, or forme fruste keratoconus were enrolled as suitable for treatment. Patients had to have a stable refractive and corneal status for 2 years.

The diagnosis of keratoconus was made by 2 or more of the following corneal observations: (1) topography map displaying I–S dioptric asymmetry of 1.50 diopters (D) or greater based on the keratoconus screening criteria developed by Rabinowitz and McDonnell[3]; (2) central or inferior corneal steepening; (3) distortion of mires on manual keratometry that indicated the presence of subtle irregular astigmatism; (4) scissors reflex on dilated retinoscopy. There were no slitlamp findings indicative of keratoconus in this study, and 2 cases reported a family history. The distinction between forme fruste and mild keratoconus was made by observing the keratometry mires, the latter displaying an inability to superimpose the corresponding distorted mires because of irregular astigmatism.

The minimum requirements to be eligible for surgical treatment included a BCVA of 20/40 or better and a nonprogressive cone displaying refractive and corneal stability for a minimum of 2 years. The minimum age was 25 years. Exclusion criteria were mean K-readings of 50.00 D, or greater BCVA worse than 20/40, signs of apical thinning, visible ectasia or scarring on slitlamp examination, and residual stromal bed less than 300 μm, assuming an epithelial thickness of 60 μm. Eyes with PMD characterized by an inferior crab-claw pattern, central flattening on topography, and an inferior band of thinning near the limbus were excluded. Studies show that eyes with advanced cones, significant thinning, and scarring are more likely to have a progression of corneal steepening and hence poorer results of surgical intervention.[11,12,22] In this study, the condition was at an early subclinical stage as no patient was aware he or she had keratoconus before the assessment for refractive laser surgery.

Patients with soft contact lenses (12 cases) were asked to cease wear 2 weeks before assessment for refractive and topographic stability and again before treatment. Patient with rigid gas-permeable lenses were asked to cease wear for a minimum of 4 weeks before assessment for stability and for another 4 weeks before treatment, at which stage refraction, topography, and keratometry were repeated for confirmation of stability before surgery.

A thorough ophthalmological assessment and examination included a case history, UCVA and BCVA with manifest and cycloplegic refractions, slitlamp microscopy, intraocular pressure, ophthalmoscopy, keratometry, topography, and ultrasonic pachymetry (DGH Technology Inc.). Various topographers were used depending on the period during which the assessment was performed. These included the Alcon EyeMap (Figure 1), introduced to the study clinic in 1994; Humphrey Atlas (Figure 3), introduced in 1999; and Bausch & Lomb Orbscan (Figure 4), introduced in 2001. Preoperative and postoperative examinations were performed using the same instruments as all had been retained for regular use.

In the consent process, patients were advised of an increased risk for the ectasia to progress in severity over time compared to the risk for an untreated cornea. Although small, the quantification of this risk is still not definable. The patients were also advised that the stability in refractive and corneal measurements in recent time did not indicate likely spontaneous progression of the keratoconus in the future.

All patients who met the inclusion criteria were included in this study. A total of 58 keratoconic eyes were treated with the Visx Star S1 excimer laser (8 eyes until 1997) or S2 excimer laser (37 eyes from 1997 forward). Thirteen eyes had PRK for simple myopia and were not included in this study. The remaining 45 eyes had PARK for myopic astigmatism and make up the group evaluated here.

The simulated keratometry value derived from the topography was incorporated into the treatment plan by calculating the ORA (ie, vectorial measure of the difference between refractive

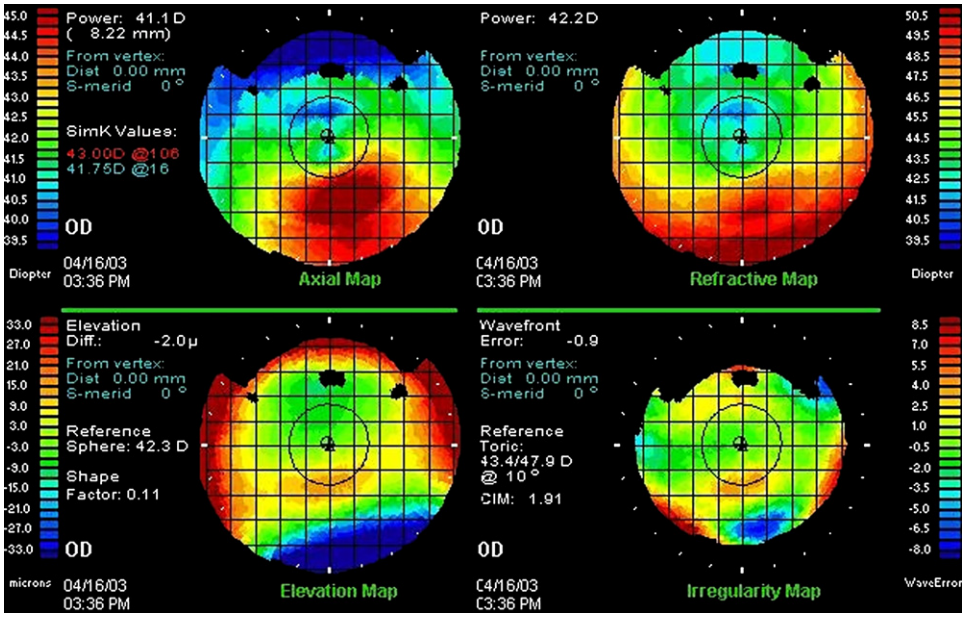

Figure 3. Atlas topography showing a keratoconus case selected for study. Note the high CIM index (1.91) irregularity map.

astigmatism and corneal astigmatism). The neutralization of this "intraocular astigmatism" occurs completely on the cornea in conventional treatments using refractive parameters alone. In this study group, all treatments were optimized, directing only part of the neutralization to the cornea and a theoretical part to the refraction, targeting 0.75 D or less remaining on the cornea and 0.50 D or less in the refraction. In cases in which the ORA was 1.50 D or more, the proportion was selected as 50% in the theoretic manifest refraction and 50% on the cornea (Figure 5), hence targeting greater amounts of remaining astigmatism than with a lower ORA.

Calculating Ocular Residual Astigmatism

Consider the example in Figure 4 with the following preoperative parameters: topography, 40.79/46.21 @ 180; corneal astigmatism, 5.42 D @ 180; refraction at the spectacle plane (back vertex distance 12.5 mm), −1.75 −2.75 × 95; refraction at the corneal plane −1.71 −2.55 × 95.

The polar diagram (Figure 2, *A*) shows 5.42 D at a meridian of 180 degrees (simulated K) and 2.55 D (positive refractive cylinder at the corneal plane) at the power axis of 5 degrees.

The double-angle vector diagram (DAVD, Figure 2, *B*) leaves the magnitudes of these parameters the same but doubles the axes, so the corneal value (simulated K) is now at 360 degrees and the refractive value is at 10 degrees on the mathematical construct.

The vectorial difference between the corneal and refractive value is the ORA (*red*), which is at 172 degrees on a DAVD. This must be halved to return to its actual orientation of 86 degrees on a polar diagram, as it would be represented on the eye (Figure 2, *C*). The calculated ORA equals 2.94 D × 86.

The clinical significance of this value is that conventional treatment using purely refractive parameters leaves corneal astigmatism

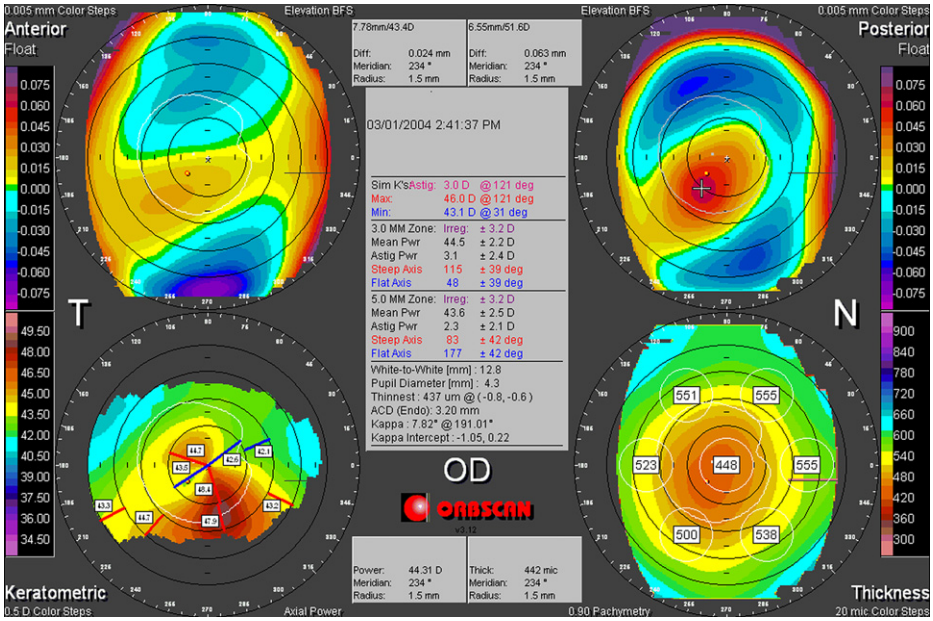

Figure 4. Orbscan map characteristic of cases selected for this study. Typical signs of keratoconus showing I–S asymmetry with thinner than average corneas; the thinnest point is decentered inferiorly, coinciding with the apex of the cone.

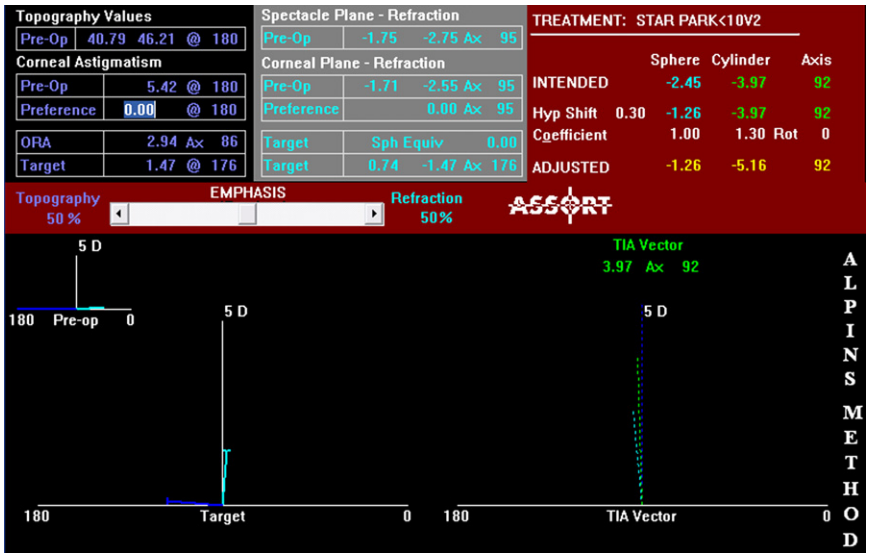

Figure 5. ASSORT treatment planning shows how the ORA of 2.94 D × 86 is apportioned 50% to eliminating the topography astigmatism and 50% to the refractive cylinder. Furthermore, this ORA is neutralized by an equivalent 1.47 D at the cornea and 1.47 D at the spectacle refraction, but at an orientation of 176 degrees.

of 2.94 D to neutralize this ORA, existing as intraocular astigmatism. This is equal in magnitude and lies on the cornea at 90 degrees to it. (This is what would theoretically be measured postoperatively by topography or keratometry if all aspects of surgery went precisely as planned.)

Vector planning reduces the corneal astigmatism component of the ORA neutralization, leaving a theoretical proportion of it to be corrected by refractive correction. In practice, this is not necessarily fully perceived by the conscious level of visual perception. Part of the net gain in the process lies in how much of this theoretical refractive cylinder is actually required to achieve the optimum visual outcome when corneal outcomes have benefited by enhanced corneal astigmatism reduction.

Statistical Analysis

All astigmatism measures in the aggregate analysis of the 45 eyes were statistically analyzed by examining the mean and the 95% confidence interval (CI). The CI is the span of measures within which one can be 95% confident to find the mean if the sample were taken from the population on a second occasion.

A further examination was performed for the correlation between analyses of changes between measurements by refraction, keratometry, and topography. The level of significance was set at a $P \leq .05$.

The Spearman correlation (r value) was used to evaluate the distribution of the variables to find the degree of covariation between the 2 distributions. An r value of 1 represents a perfect alignment.

All calculations were performed using ASSORT planning and outcomes analysis software.

Surgical Technique

The surgical technique included the use of an Amoils Epithelial Scrubber (Innova Inc.) followed by multizone/multipass[23] laser ablation, cold balanced salt solution, diclofenac sodium 5 mg/mL (Voltaren Ophtha), chloramphenicol 5 mg/mL (Chlorsig), and a bandage contact lens (J&J disposable), which was removed once the epithelium had healed 2 or 3 days postoperatively. Medications prescribed were Chlorsig 4 times a day for approximately 1 week and upon healing of the epithelium, fluorometholone 1 mg/mL (FML) 4 times a day tapered weekly for 1 month. Carboxymethylcellulose sodium 5 mg/mL (Cellufresh lubricating drops) were used over the month.

Postoperative Follow-up

Postoperative examinations were performed at 1, 2, and 3 days, and in some cases 4 days if the epithelium had not completely healed by day 3, and also at 1, 3, 6, and 12 months. Reminder notices were sent to the patients at 5 years and 10 years.

RESULTS

Forty-five eyes of 29 patients (20 women and 9 men) with forme fruste or mild keratoconus were treated for myopic astigmatism. Twenty-one eyes had forme fruste keratoconus, and 24 eyes had mild keratoconus. The mean age was 40 years (range 27 to 58 years). Another 13 eyes of 10 patients (8 women, 2 men) with forme fruste or mild keratoconus were treated for myopia alone with similar favorable outcomes (mean sphere at 12 months −0.08 DS ± 0.24 [SD], UCVA and BCVA 20/30 or better) and are not included further.

The number of patients available for analysis diminished over time because the postoperative period had not elapsed (13 eyes at 5 years; 34 eyes at 10 years) or there was loss of contact (2 eyes of 1 patient at 10 years). The group continues to be monitored for corneal stability using the Atlas, EyeMap, or Orbscan, for manifest refraction, and for keratometry readings, with postoperative results grouped into 1 year, 5 years, and 10 years; the first patients treated in 1996 (9 eyes) now have a follow-up of more than 10 years. No treated eye has progressed to clinically evident keratoconus.

The mean preoperative astigmatism measured by manifest refraction (−1.39 ± 1.08 D C), keratometry

(1.52 ± 1.18 D), and topography (1.70 ± 1.42 D) were similar. One year postoperatively, the mean astigmatism was −0.43 ± 0.40 D C, 1.05 ± 0.85 D, and 1.02 ± 0.83 D, respectively (Table 1, Figure 6). There was no statistical difference in corneal and refractive outcomes between the forme fruste group and mild keratoconus group, so the 2 groups were examined together.

Forty-five eyes were reviewed 1 year, 32 eyes 5 years, and 9 eyes 10 years postoperatively for stability of the corneal astigmatism (by keratometry) (Figure 7) and refractive cylinder measurements (Figure 8).

The mean spherical equivalent was −3.94 ± 1.87 DS preoperatively and −0.23 ± 0.52 D S 12 months postoperatively. The mean preoperative ORA was 1.34 ± 1.00 D (range 0.23 to 4.37 D), and the ORA decreased over time (Table 2).

The mean correlating irregularity quantified by topographic disparity was 2.32 ± 1.84 D (range 0.50 to 5.33 D) preoperatively.

The mean pachymetry preoperatively was at 497 µm (range 447 to 534 µm). The mean decreased to 462 µm (range 402 to 483 µm) postoperatively.

Table 1. Mean astigmatism by refraction, keratometry, and topography over time.

Astigmatism	Refraction (DC)	Keratometry (D)	Topography (D)	*r* Value, *P* Value
1 year (n = 45)				
Preoperative				
Mean ± SD	−1.39 ± 1.08	1.52 ± 1.18	1.70 ± 1.42	K/T 0.81, <.001
CI	−0.75 to 3.53	−0.82 to 3.86	−1.08 to 4.47	R/T 0.39, 0.01
Postoperative				
6 months				
Mean ± SD	−0.43 ± 0.49	1.18 ± 0.83	0.99 ± 0.43	NS
CI	−0.55 to 1.41	−0.48 to 2.83	+0.14 to 1.84	
12 months				
Mean ± SD	−0.43 ± 0.40	1.05 ± 0.85	1.02 ± 0.83	K/T 0.51, <.001
CI	−0.42 to 1.29	−0.64 to 2.75	−0.62 to 2.66	
5 years (n = 32)				
Preoperative				
Mean ± SD	−1.61 ± 1.18	1.74 ± 1.27	2.05 ± 1.54	R/K 0.404, .02
CI	−0.74 to 3.92	−0.75 to 4.23	−1.05 to 4.99	R/T 0.512, .002
Postoperative				K/T 0.857, <.001
6 months				
Mean ± SD	−0.37 ± 0.49	1.30 ± 0.91	1.19 ± 0.72	N/S
CI	−0.60 to 1.32	−0.52 to 3.08	+0.07 to 1.84	
12 months				
Mean ± SD	−0.43 ± 0.41	1.17 ± 0.91	1.13 ± 0.89	K/T 0.555, <.001
CI	−0.37 to 1.24	−0.60 to 2.96	−0.75 to 2.83	
5 years				
Mean ± SD	−0.37 ± 0.45	1.22 ± 0.89	1.15 +/ 0.92	K/T 0.906, <.001
CI	−0.51 to 1.23	−0.59 to 2.95	−0.70 to 2.93	
10 years (n = 9)				
Preoperative				
Mean ± SD	−2.07 ± 1.16	2.11 ± 1.31	2.28 ± 1.25	K/T 0.845, .004
CI	−0.35 to 4.48	−0.62 to 4.84	−0.69 to 5.34	
Postoperative				
6 months				
Mean ± SD	−0.49 ± 0.75	1.46 ± 1.24	0.85 ± 0.51	NS
CI	−1.07 to 2.05	−1.12 to 4.03	+0.19 to 1.94	
12 months				
Mean ± SD	−0.65 ± 0.32	1.35 ± 1.27	1.35 ± 1.17	K/T, 0.870, .002
CI	−0.02 to 1.33	−1.29 to 6.45	−0.87 to 3.60	
10 years				
Mean ± SD	−0.52 ± 0.39	1.25 ± 1.06	1.24 ± 1.15	K/T 1.00, <.001
CI	−0.30 to 1.34	−0.96 to 3.46	−1.08 to 3.56	

CI = 95% confidence interval; K = keratometry; NS = no significance; R = refraction; T = topography

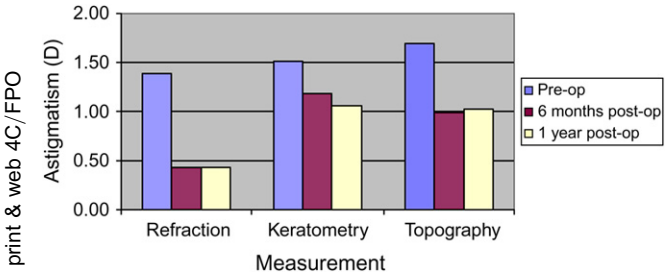

Figure 6. Reduction in refractive and corneal astigmatism in the 45 eyes 1 year postoperatively.

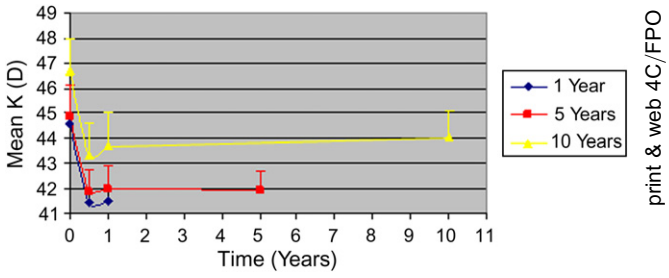

Figure 7. Stability of the cornea over time by consistency of mean keratometry values over time.

One year postoperatively, the Snellen UCVA was 20/40 or better in all eyes, 20/30 or better in 89% of eyes, and 20/20 or better in 56% of eyes. The BCVA preoperatively and at 1 year was 20/20 or better in 89% of eyes and 20/30 or better in all eyes (Figure 9).

More eyes gained BCVA than lost BCVA. One eye had a 2-line loss, 6 eyes had a 1-line loss, 22 eyes were unchanged, 13 eyes had a 1-line gain, and 3 eyes had a 2-line gain (Figure 10).

Astigmatic vector analysis results using the difference vector (quantifying absolute error) in all 45 cases are shown individually on a polar diagram in Figure 11; the mean by topography was 0.84 D at 1 year. The summated vectorial mean of 0.09 D × 6 indicates little overall trend in error and a high degree of success in the amount of astigmatism correction attempted in each eye.

The correction index indicates an overall undercorrection of astigmatism with all 3 modalities (refraction, keratometry, and topography) of approximately 25% for the group; this is reflected in the small negative magnitude of error outcomes (Table 3). The significant angle of error (absolute) of approximately 18 degrees, and hence higher than the optimum index of success, explains how future treatments may be assisted with tracking devices that are now standard with all excimer laser systems.

DISCUSSION

Keratoconus most commonly presents subclinically as an isolated sporadic disorder with no other associated systemic or ocular disease. The irregular corneal shape is known to be a consequence of the altered biomechanics caused by defects of Bowman's layer and associated inferior corneal thinning.[24] Approximately 6% to 8% of keratoconus patients have a family history,[25] and while findings are consistent with autosomal-dominant inheritance, penetrance and variable expressivity are incomplete.[26,27]

Patients evaluated for PRK should be carefully selected[28,29] and followed over time to determine stability of manifest refraction and corneal topography. This is to ensure any eye with progressive or unstable disease is excluded from surgical intervention.

Eyes with mild or forme fruste keratoconus have, in general, a poorer correlation between corneal and refractive values than eyes in a normal astigmatic population.[21] This is quantified by the ORA,[17,21] and the eye's optical system cannot be corrected completely by laser treatment. In our group of keratoconic patients, the mean ORA (1.34 D, Table 2) was almost 60% greater than that in healthy astigmatic eyes in 2 other series (0.73 D[16] and 0.81 D[17]). Consequently the topographic disparity was also very much in excess of the average value 1.10 ± 0.08 D in 100 normally astigmatic eyes having PARK.[21]

Ideally, when both corneal and refractive values are examined, the amount of astigmatism remaining in the eye's optical system postoperatively should be zero. However, this would only be possible when the corneal cylinder and refractive cylinder (at the corneal plane) match each other exactly in magnitude and axis. Given that this is extremely rare, a minimum amount of astigmatism usually remains postoperatively. That is, the refractive cylinder, measured by manifest refraction or in recent times by wavefront aberrometry, does not coincide in magnitude and/or axis to the amount

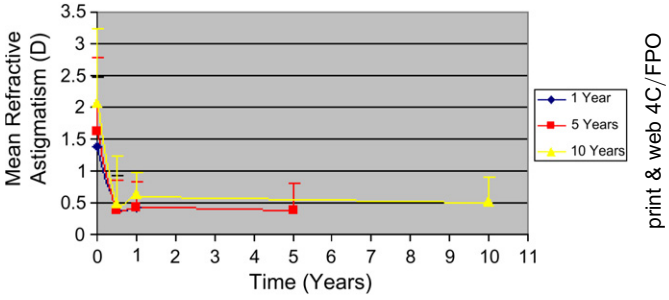

Figure 8. Refractive astigmatism stability over time in the 1-year, 5-year, and 10-year groups.

Table 2. Spherical equivalent, keratometry, and ORA over time.

Measurement	Spherical Equivalent (DS)	Keratometry (D)	ORA (D)
1 year (n = 45)			
Preoperative			
Mean ± SD	−3.94 ± 1.87	44.56 ± 1.18	1.34 ± 1.00
Range	−0.75 to −9.63	40.70 to 47.50	0.19 to 4.37
Postoperative			
6 month			
Mean ± SD	−0.13 ± 0.54	41.45 ± 0.83	1.14 ± 0.88
Range	−0.75 to +0.75	35.87 to 46.75	0.19 to 3.02
1 year			
Mean ± SD	−0.23 ± 0.52	41.46 ± 0.85	1.00 ± 0.78
Range	−1.25 to +0.63	37.43 to 47.50	0.00 to 2.04
5 years (n = 32)			
Preoperative			
Mean ± SD	−3.55 ± 1.59	44.85 ± 1.27	1.40 ± 1.08
Range	−1.13 to −6.88	40.70 to 4.75	0.30 to 4.37
Postoperative			
1 year			
Mean ± SD	−0.25 ± 0.53	41.97 ± 0.91	1.12 ± 0.84
Range	−1.25 to +0.38	37.43 to 46.31	0.00 to 2.08
5 years			
Mean ± SD	−0.13 ± 0.38	41.91 ± 0.89	1.06 ± 0.83
Range	−1.25 to +0.25	37.63 to 46.50	0.10 to 2.67
10 years (n = 9)			
Preoperative			
Mean ± SD	−4.19 ± 1.80	46.68 ± 1.31	1.53 ± 1.50
Range	−2.00 to −6.88	41.75 to 49.94	0.50 to 4.02
Postoperative			
1 year			
Mean ± SD	−0.47 ± 0.84	43.72 ± 1.27	1.43 ± 1.33
Range	−1.25 to +0.63	40.75 to 47.50	0.30 to 2.08
10 years			
Mean ± SD	−0.29 ± 0.64	44.01 ± 1.06	1.40 ± 1.29
Range	−1.25 to +0.50	40.60 to 47.61	0.29 to 2.89

ORA = ocular residual astigmatism

of corneal astigmatism or its meridian, as measured by videokeratography or keratometry[21] (D. Burger et al., "Keratoconus: Diagnosis and Management," Pacific University College of Optometry 2003 [online]. Available at: www.opt.pacificu.edu/ce/catalog/web013/course.htm. Accessed December 16, 2006).

In this commonly prevailing situation, conventional treatment using parameters by manifest refraction values alone will leave an excess amount of astigmatism on the cornea.[17] In keratoconus, this is evidenced by the greater than average calculated ORA in any group of eyes having treatment for astigmatism with myopia. Conversely, treating by corneal data alone will attempt to make the cornea more spherical; however, this will leave excess astigmatism measurable in the manifest refraction postoperatively, which is likely to be unacceptable to the patient.

The technique of vector planning incorporates both corneal topographical data and refractive astigmatism data in the treatment plan. Reduction in corneal astigmatism expected to remain by more closely aligning the maximum ablation to the principal (flat) corneal meridian will create less off-axis effect. In this way, the corneal shape changes more favorably, with less astigmatism remaining. The treatment is less likely to create distortion of optics resulting from excess cross-cylinder effect induced by the change. The reduction in corneal astigmatism substantially exceeds the increase in measurable refractive cylinder. This has the overall effect of minimizing the total amount of astigmatism (refractive + topographic) after laser surgery that is required to neutralize the ORA. This phenomenon is effectively demonstrated by examining a case study of 1 eye of 1 patient in the study.

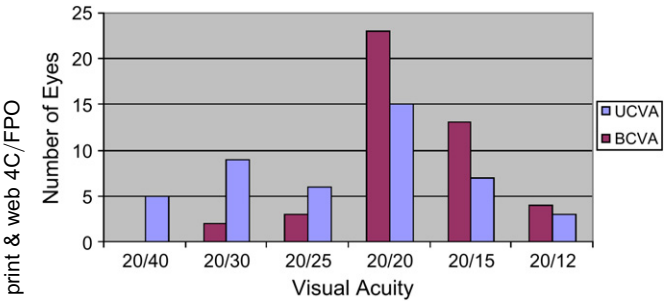

Figure 9. The UCVA and BCVA 1 year postoperatively. All eyes had an UCVA of 20/40 or better and a BCVA of 20/30 or better.

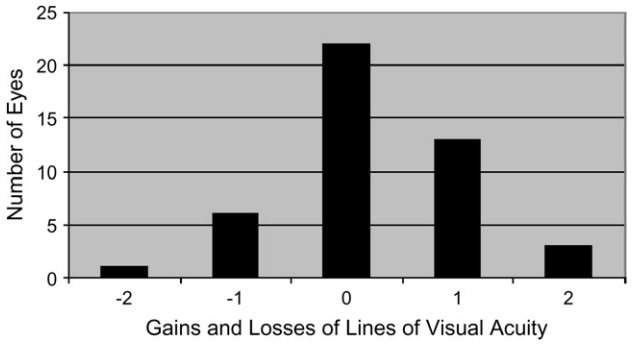

Figure 10. Gains and losses in BCVA 1 year postoperatively.

Individual Outcome: Case Study

Consider the parameters in Figure 5. There is 2.94 D of astigmatism (ie, the ORA that was calculated in Figure 2) that theoretically cannot be eliminated from this optical system. If treatment were based solely on refractive parameters, the 2.94 D would be destined to remain entirely on the cornea.

The treatment plan actually used shared the attempted elimination of astigmatism equally, with 50% emphasis on the theoretical reduction of both topographic and manifest refractive astigmatism instead of 100% on refractive astigmatism. So theoretically, 1.47 D might be expected to remain on the cornea and 1.47 D to remain in the manifest cylinder postoperatively.

To correct the existing ORA by reshaping the surface of the eye, the corneal astigmatism magnitude is equivalent but its orientation on the cornea and/or in the spectacles (negative cylinder) is 176 degrees, 90 degrees away from the ORA axis of 86 degrees. Any remaining (negative) refractive cylinder is expected at the same orientation of 176 degrees.

In practice, 12 months postoperatively, the patient achieved the expected 1.50 DC on the cornea but only 0.50 D in the spectacle refraction, so not only did the corneal astigmatism reduce from 5.42 D to 1.50 D beyond the 2.94 D if treating by refractive values alone, but excess amount of astigmatism in the spectacle refraction was avoided by the advantages of less corneal astigmatism on a keratoconic cornea. This favorable outcome was common in many cases in the group and is also evident in the aggregate results.

This patient also had an improvement in BCVA, from 20/15 to 20/12 (Table 4), as well as improved UCVA, from 20/120 to 20/15.

Group Outcomes

The mean ORA in the 45 eyes treated for myopic astigmatism was calculated as 1.34 D. By neutralising only part of the ORA on the cornea instead of total, the average optimized distribution for the group was 36% emphasis placed on eliminating corneal astigmatism (simulated keratometry) and 64% on manifest cylinder instead of the customary 100%. This division of the ORA between cornea and refraction was optimized for each case, with the aim of minimizing the expected (target) astigmatic outcome for both the cornea and the manifest refraction and favoring the remaining corneal astigmatism to a with-the-rule orientation when it occurred (range 67% topography/33% refraction to 2% topography/98% refraction).

Using the expected corneal and refractive targets (calculated using ASSORT program) resulting from the apportioning of the ORA in each case, the mean topography target in the group was calculated as 0.75 $\pm$ 0.46 D and the mean refractive target as -0.59 ± 0.56 DC (Table 5). For simplicity and to avoid too many numerics, the results achieved by topography can be examined (keratometry values would come to a parallel conclusion) 1 year postoperatively. At this visit, mean astigmatism was 1.02 D by topography and -0.43 DC

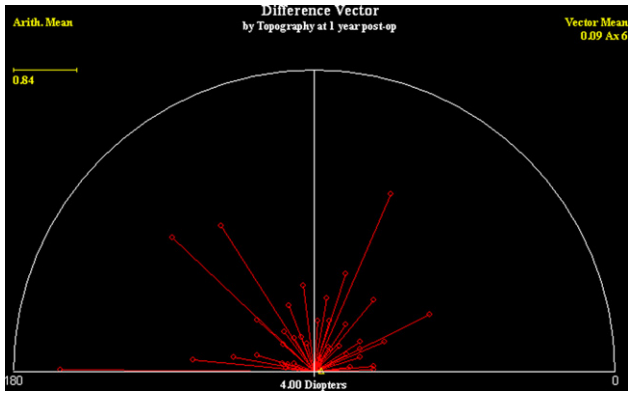

Figure 11. Vector graph showing the individual difference vectors by topography (an absolute dioptric measure of error) and the summated vector mean in the 45 eyes 1 year postoperatively.

Table 3. Vector analyses by refraction, keratometry, and topography 1 year postoperatively (n = 45).

Vector Analysis	Refraction	Keratometry	Topography	*r* Value, *P* Value
Correction index				
Mean ± SD	0.74 ± 4.29	0.72 ± 2.17	0.77 ± 1.89	K/T 0.59, <.001
95% CI	−0.22 to 2.28	−0.63 to 2.55	−0.25 to 2.12	
Index of success				
Mean ± SD	0.55 ± 0.12	0.89 ± 0.10	0.66 ± 0.11	R/T 0.38, .01
95% CI	−0.60 to 1.93	−0.47 to 2.45	−0.53 to 2.06	
Absolute angle of error (degrees)				
Mean ± SD	13.80 ± 14.53	22.75 ± 16.97	18.73 ± 20.47	NS
Arithmetic angle of error (degrees)				
Mean ± SD	3.94 ± 19.65	9.79 ± 26.64	−6.72 ± 26.92	K/T 0.65, <.001
95% CI	−14.99 to 42.60	−10.90 to 56.39	−21.84 to 59.31	
Magnitude of error (D)				
Mean ± SD	−0.17 ± 0.68	−0.39 ± 0.81	−0.19 ± 0.65	
95% CI	−1.52 to 1.17	−1.99 to 1.21	−1.48 to 1.11	

CI = confidence interval; K = keratometry; NS = no significance; R = refraction; T = topography

by manifest refraction. This difference of 0.27 D between the 1.02 D actually achieved by topography and the mean target topography of 0.75 D can be attributed to commonly prevailing healing effects and treatment factors associated with the ablation causing a less than perfect outcome.

In view of previously reported negative experiences or adverse outcomes when treatment for keratoconic corneas was defined by refractive values alone, there was no control group in this study. An attempt to determine the projected outcomes in such a group can be theoretically extrapolated in the following manner: Treatment by refraction alone would have resulted in the entire ORA (1.34 D) plus the average healing factor of 0.27 D (from the 1-year postoperative data), predicting that a mean 1.61 D in each patient in the study group would have remained on the cornea postoperatively compared to the 1.02 D achieved (Table 5).

The same 0.27 D of healing factors would reasonably be expected to translate to the refractive astigmatism result. Hence, we would expect −0.59 DC (mean target refraction) plus −0.27 D = −0.86 DC. Instead, the mean refractive astigmatism 12 months postoperatively was −0.43 DC, so the refractive outcomes were not compromised; in fact, the opposite

Table 4. Individual outcomes of a patient with form fruste keratoconus.

Left Eye	UCVA	BCVA	Manifest Refraction	Corneal Astigmatism (D)
Preop	20/120	20/15	−1.75 −2.75 × 95	5.42 @ 180
3 month postop	20/15	20/10	Plano −0.50 × 160	1.50 @ 20

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

Table 5. Astigmatic outcomes at 1 year (n = 45) using refraction plus topography parameters in the treatment (vector planning) compared to theoretical treatment by refraction alone.

Mean Astigmatism (n = 45)	Topography (D)	Refraction (DC)
ORA	1.34 ± 1.00	
Expected targets using 64% refraction and 36% topography emphasis in treatment plan	0.75 ± 0.46	−0.59 ± 0.56
Expected targets using 100% Refraction alone in treatment plan	1.34	0.00
Postop (1 year)	1.02 ± 0.83	−0.43 ± 0.40
Healing and treatment factors	0.27 (1.02 achieved – 0.75 expected on the cornea)	
Theoretical outcome including healing factors by 100% refraction treatment	1.61 (1.34 + 0.27)	0.27 (healing factors)

Means ± SD

occurred with an achieved enhanced optimized refractive cylinder outcome. Without healing and treatment factors, the potential refractive astigmatism could have been as low as 0.16 D (0.43 D – 0.27 D).

The UCVA was 20/20 or better in 56% of eyes and 100% 20/40 or better in all eyes (Figure 9). Seven eyes lost BCVA, and 16 eyes gained BCVA (Figure 10).

The stability of corneal and refractive astigmatism over time is shown in Figures 5 and 6, over a period of 10 years in some cases, with no evidence of progression of the keratoconus.

Figure 11 shows the difference vector, which is the vectorial difference between the target induced astigmatism vector and the surgically induced astigmatism vector.[30] The difference vector is a precise measure of unplanned astigmatic error. In this group of 45 eyes, the mean magnitude by topography was 0.84 D and the summated vector mean (centroid)[18] was calculated to be 0.09 D $\times$ 6, indicating an insignificant amount of aggregate error postoperatively in the entire group.

With the introduction of aberrometry, it will now be possible to quantify higher-order aberrations (HOAs) (3rd-order coma and trefoil in particular) preoperatively and postoperatively. One would expect these HOAs to be smaller in magnitude in eyes treated using vector planning because of the lower amount of corneal astigmatism remaining postoperatively and hence the better visual outcomes, particularly evident under the sensitivity provided in low-contrast conditions.

CONCLUSION

This treatment paradigm of combining corneal (topography or keratometry) parameters with refractive measurements for correcting astigmatism in cases of mild or forme fruste keratoconus using PARK was safe and effective in 45 eyes. These eyes had a stable refraction and corneal topography over an extended period of time, up to 10 years postoperatively. This was true in terms of nonprogression of the disease and favorable spherical and astigmatic refractive outcomes. No problems or adverse signs such as an increase in corneal irregularity or progression of ectasia resulting in a reduction in UCVA or BCVA were detected.

Treating forme fruste and mild keratoconic patients by PARK using conventional means (ie, refraction parameters) alone would cause an excess amount of corneal astigmatism to remain that would have potential adverse effects. This excess astigmatism has an irregular component and together may be responsible for adverse outcomes reported in a proportion of these patients. The hesitancy in treating such patients with excimer laser systems is sensible in these circumstances. However, treating such irregular astigmatic corneas using vector planning that integrates topographic values can result in less corneal astigmatism without compromising the refractive outcome. This more effectively reduces overall remaining astigmatism, as evidenced by quantifying the combined amount of corneal and refractive astigmatism. The potential for reduced HOAs (coma and trefoil) exists with a greater likelihood to achieve an improved BCVA more frequently and avoid adverse symptomatic effects.

REFERENCES

1. Ridley F. Contact lenses in treatment of keratoconus. Br J Ophthalmol 1956; 40:295–304
2. Amsler M. Le Kératocône fruste au Javal. Ophthalmologica 1938; 96:77–83
3. Rabinowitz YS, McDonnell PJ. Computer-assisted corneal topography in keratoconus. Refract Corneal Surg 1989; 5:400–408
4. Smolek MK, Klyce SD. Current keratoconus detection methods compared with a neural network approach. Invest Ophthalmol Vis Sci 1997; 38:2290–2299
5. Rabinowitz YS, Rasheed K. KISA% index: a quantitative videokeratography algorithm embodying minimal topographic criteria for diagnosing keratoconus. J Cataract Refract Surg 1999; 25:1327–1335; errata 2000; 26:480
6. Maeda N, Klyce SD, Smolek MK, Thompson HW. Automated keratoconus screening with corneal topography analysis. Invest Ophthalmol Vis Sci 1994; 35:2749–2757
7. Oshika T, Tanabe T, Tomidokoro A, Amano S. Progression of keratoconus assessed by Fourier analysis of videokeratography data. Ophthalmology 2002; 109:339–342
8. Durand L, Monnott J-P, Burillon C, Assi A. Complications of radial keratotomy eyes with keratoconus and late wound dehiscence. Refract Corneal Surg 1992; 8:311–314
9. Ellis W. Radial keratotomy in a patient with keratoconus. J Cataract Refract Surg 1992; 18:406–409
10. Malecaze F, Coullet J, Calvas P, et al. Corneal ectasia after photorefractive keratectomy for low myopia. Ophthalmology 2006; 113:742–746
11. Mortensen J, Öhrström A. Excimer laser photorefractive keratectomy for treatment of keratoconus. J Refract Corneal Surg 1994; 10:368–372
12. Kremer I, Schochot Y, Kaplan A, Blumenthal M. Three year results of photoastigmatic keratectomy for mild and atypical keratoconus. J Cataract Refract Surg 1998; 24:1581–1588
13. Sun R, Gimbel HV, Kaye GB. Photorefractive keratectomy in keratoconus suspects. J Cataract Refract Surg 1999; 25: 1461–1466
14. Bilgihan K, Özdek SC, Konuk O, et al. Results of photorefractive keratectomy in keratoconus suspects at 4 years. J Refract Surg 2000; 16:438–443
15. Kasparova EA, Kasparov A. six-year experience with excimer laser surgery for primary keratoconus in Russia. J Refract Surg 2003; 19:S250–S254
16. Alpins NA. New method of targeting vectors to treat astigmatism. J Cataract Refract Surg 1997; 23:65–75
17. Alpins N. Astigmatism analysis by the Alpins method. J Cataract Refract Surg 2001; 27:31–49
18. Holladay JT, Moran JR, Kezirian GM. Analysis of aggregate surgically induced refractive change, prediction error, and intraocular astigmatism. J Cataract Refract Surg 2001; 27:61–79

19. Gündüz A, Evereklioglu C, Er H, Hepşen IF. Lenticular astigmatism in tilted disc syndrome. J Cataract Refract Surg 2002; 28:1836–1840
20. Spiegel D, Widmann A, Köll R. Noncorneal astigmatism related to poly(methyl methacrylate) and plate-haptic silicone intraocular lenses. J Cataract Refract Surg 1997; 23:1376–1379
21. Alpins NA. Treatment of irregular astigmatism. J Cataract Refract Surg 1998; 24:634–646
22. Mortensen J, Carlsson K, Ohrstrom A. Excimer laser surgery for keratoconus. J Cataract Refract Surg 1998; 24:893–898
23. Alpins NA, Taylor HR, Kent DG, et al. Three multizone photorefractive keratectomy algorithms for myopia; the Melbourne Excimer Laser Group. J Refract Surg 1997; 13:535–544
24. Edmund C. Corneal topography and elasticity in normal and keratoconic eyes. A methodological study concerning the pathogenesis of keratoconus. Acta Ophthalmol Suppl 1989; 193
25. Rabinowitz YS, Maumenee IH, Lundergan MK, et al. Molecular genetic analysis in autosomal dominant keratoconus. Cornea 1992; 11:302–308
26. Davis LJ. Keratoconus: current understanding of diagnosis and management. Clin Eye Vis Care 1997; 9:13–22
27. Rabinowitz YS. Keratoconus. Surv Ophthalmol 1998; 42: 297–319
28. Binder PS, Lindstrom RL, Stulting RD, et al. Keratoconus and corneal ectasia after LASIK [letter]. J Cataract Refract Surg 2005; 31:2035–2038
29. Colin J, Velou S. Current surgical options for keratoconus. J Cataract Refract Surg 2003; 29:379–386
30. Alpins NA. A new method of analyzing vectors for changes in astigmatism. J Cataract Refract Surg 1993; 19:524–533

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