Refractive versus Corneal Changes After Photorefracive Keratectomy for Astigmatism

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ABSTRACT

PURPOSE: To define measures of assessing success and subsequent ways to improve excimer laser treatment of astigmatism.

METHODS: We studied 97 eyes of 79 patients, followed for 12 months, that underwent photorefractive keratectomy (PRK) for myopia and astigmatism with a VISX 20/20 excimer laser. Preoperative spherical equivalent refraction at the corneal plane was between -1.00 and -15.00 D. Mean preoperative refractive astigmatism at the spectacle plan was -2.17 ± 1.05 D (range, -1.25 to -6.00 D), which is -1.81 ± 0.86 D (range -1.04 to -4.97 D) when calculated at the corneal plane. All patients were examined before and after surgery; examination included refraction, keratometry, and topography measurement.

RESULTS: The success in treatment of astigmatism appeared measurably less than the treatment of sphere when analogous indices were used for assessment. Success in astigmatism surgery improved, as measured by all parameters, after an additional 20% was applied to astigmatism treatment magnitude indicated by the VISX computer algorithm. The sequential modes of treatment undercorrected astigmatism magnitude to a greater extent than elliptical, but equivalent success rates were present in view of the greater astigmatic changes attempted using the sequential mode. The elliptical mode tended to produce a greater undercorrection of associated sphere (p=0.313). Results measured by refraction showed a larger change than those measured by topography and keratometry.

CONCLUSION: During PRK with the VISX 20/20 laser, adjustment for undercorrection of astigmatism treatment achieves a fuller correction of astigmatism. When measuring astigmatic changes, results are different when comparing refractive astigmatism changes with corneal astigmatism changes measured by keratometry and topography. [*J Refract Surg* 1998;14:386-396]

Reported results from photorefractive keratectomy (PRK) for spherical myopia have shown high levels of successful visual outcomes.[1-2] Reports of the visual outcome of the correction of myopic astigmatism (PARK) have also been encouraging.[3-12] However, the major proportion of visual improvement has been the result of improving the patient's spherical refraction.[13] If one examines the changes in induced astigmatism, it appears the success in treating astigmatism may not approach that achieved when treating spherical myopia.

This study uses the method developed by the first author (Alpins) to comprehensively determine the success of astigmatism treatment, the errors occurring, and the necessary adjustments to achieve better performance.[8] It contains an integrated analysis of astigmatism using both vector and simple (non-vector) analysis by measurement of refraction, keratometry, and corneal topography. It compares success for astigmatism treatment with that of spherical treatment using comparable indices.

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PATIENTS AND METHODS

Patient Selection

Patients eligible for inclusion underwent treatment for astigmatism of greater than 1.00 diopter (D) at the corneal plane and measurement data was available for three parameters of astigmatism measurement—refraction, keratometry, and topography. The patients were 18 years of age or older; had given informed consent to the surgery; had stable myopia of less than -18.50 D sphere at the spectacle plane with stable astigmatism of up to -6.00 D cylinder, and had spectacle-corrected visual acuity of 20/60 or better in both eyes. If the patient wore contact lenses regularly, then a stable refraction was confirmed after discontinuing soft contact lens wear for 1 week or after ceasing hard contact lens wear for 2 months. Availability for follow-up for at least 1 year after surgery was required. There were 97 eyes in the study; 45 from males and 52 from females. The 79 patients had an average age of 44.4 years. The Human Research Ethics Committee of the Royal Victorian Eye and Ear Hospital in Melbourne, Australia approved the study protocol and informed consent procedures.

Excimer Laser Treatment

A VISX Twenty/Twenty excimer laser (VISX Inc., Sunnyvale, Calif) version 2.7 software was used for PARK in this study. One of two methods was used for the treatment of myopic astigmatism—sequential or elliptical. In the sequential method, the treatment for myopia and astigmatism was performed in two phases; first as a plano-cylindrical ablation to correct the astigmatic component, followed by a second ablation to correct the remaining spherical myopia. The amount of minus sphere to be treated was calculated by first determining the expected hyperopic shift that would result from the myopic astigmatism correction. This is necessary because the plano-cylindrical correction removes more tissue than the elliptical when treating astigmatism, resulting in greater flattening of the central cornea. The hyperopic shift is calculated by subtracting 1.00 D from the amount of cylinder and then halving the remaining amount of cylinder to provide a spherical equivalent value.[8] This amount of expected hyperopic shift is then subtracted from the spherical myopia component to be corrected, to give the net targeted spectacle myopia for treatment. With the elliptical method, the concurrent expansion of the parallel blades and controlled contraction of the round diaphragm achieve a full myopic and astigmatic correction sculpted onto the cornea in one smooth ablation. No correction for hyperopic shift is required.

Keratometry power was measured, and corneal topography data were taken and recorded as determined by the simulated keratometry value utilizing the TMS-1 Topographic Modeling System version 1.41 (Computed Anatomy, Inc., New York, NY). The refractive error to be corrected was determined by manifest refraction and confirmed by cycloplegic refraction. When cycloplegic refraction differed significantly from manifest refraction, then the manifest refraction was repeated on another day to re-evaluate the parameters for treatment. Manifest refraction was treated in the majority of eyes where certainty of end-point was achieved, as this was considered to be the more appropriate treatment parameter. The spectacle correction was then converted to the corneal plane and the desired refractive corrections and cylinder magnitude and axis were entered into the controlling software, using the following zonal distribution paradigm. The Melbourne Excimer Laser Group multizone treatment algorithm was used for the correction of myopic astigmatism procedures. For corrections of -5.00 D or less spherical equivalent (low myopia), a single 6.0 mm diameter ablation zone was used. For corrections greater than -5.00 D spherical equivalent and less than or equal to -10.00 D spherical equivalent (high myopia), two zones were used (5.0 mm and 6.0 mm diameters); and for corrections greater than -10.00 D (extreme myopia), three zones (4.5mm, 5.0 mm, and 6.0 mm diameters) were used. The spherical myopic correction was divided equally into each zone. Equal dioptric distribution was preferred as ablation profiles with this technique are considered to have smooth transition zones.

When an elliptical astigmatic correction was performed, the cylindrical portion of the treatment up to 80% of the dioptric power of the associated sphere was entered into the largest (6.0 mm) ablation diameter size. When cylinder exceeded 80% of the sphere to be treated in the 6.0 mm zone, the astigmatic correction was shared equally between the 5.0 mm and 6.0 mm zones in order to prevent overlapping boundaries and create concentric ellipses and evenly contoured craters. The effect of this is to maintain less narrowing of the minor axis of the ellipse. No astigmatism was corrected in the 4.5 mm zone even when this zone was employed for part of the correction of spherical equivalents greater than -10.00 D.[9] This was to avoid the minor axis of the ellipse being less than this minimum diameter and to avoid symptoms due to inadequately sized ablation zones. Patients were treated by one of 27 surgeons, who followed the same protocol. The excimer laser surgery was performed under topical anesthesia (1% amethocaine hydrochloride with or without 4% lidocaine hydrochloride [Xylocaine]). The eyes were kept open with a light-guarded speculum retracting the eyelids. The epithelium was debrided with either a Paton's spatula or a dulled Beaver blade. The surgeon determined fixation; patient fixation, limbal suction ring, or forceps fixation was used.

Ablations were performed using a fluence of 160 mJ/cm^2 at a repetition rate of 5 Hz. Nitrogen gas was not blown over the cornea. A vacuum suction system was used to remove ablated debris. At the completion of treatment, the ablated surface was moistened with a drop of 2% homatropine; 1% chloramphenicol ointment was placed in the eye, and the eye was covered with a semi-pressured patch. The eye was first examined 1 to 2 days following surgery. Antibiotic ointment was continued until after re-epithelialization was complete and then 0.1% topical fluorometholone drops were started four times a day for 1 month. Fluorometholone was then reduced by one drop per day each month over the next 3 months after which it was discontinued.

Examination Protocol

A standardized examination protocol was followed for all patients. All 79 patients were followed for 12 months. Uncorrected and best spectacle-corrected visual acuity were determined by using a logMAR chart. The logMAR chart acuities were directly converted to the equivalent Snellen acuities. Corneal haze included both the initial inflammatory infiltrate and tissue swelling and later corneal scarring into which the initial changes may blend imperceptibly over time. Haze was graded using a five-point subjective scale. Haze of 2 or greater was considered an adverse reaction. Increased intraocular pressure or decentration deemed clinically significant by the treating surgeon was recorded as an adverse reaction. All patients in the study group had subjective refraction, keratometry, and topographical corneal mapping by videokeratography. The same types of keratometer, either Bausch & Lomb or Haag-Streit, were used for measurement of preoperative and postoperative keratometry, with the same technicians responsible for readings in each group. The same technicians also performed the subjective refractions. Staff at a centrally located laser center performed corneal topography.

Data Analysis

The Alpins method of astigmatism analysis[13] was used to evaluate the changes in astigmatism induced by treatment. The ASSORT (Alpins Statistical System for Ophthalmic Refractive Surgery Techniques) outcomes analysis software was used to perform vector analysis on the astigmatism data. The calculations were performed for the subjective refractive measurements converted to the corneal plane and both the objective measurements of topography and keratometry. The Targeted Induced Astigmatism (TIA) is the vector of intended change in cylinder for each treatment. The Surgically Induced Astigmatism (SIA) is the vector of the actual change that occurred. The correction index is the surgically induced astigmatism divided by the targeted induced astigmatism and a percentage value astigmatism correction achieved can be obtained by multiplying this number by 100. The magnitude and angle of error is the arithmetic difference between the surgically induced astigmatism and targeted induced astigmatism magnitude and axis values, respectively. The difference vector (DV) is the astigmatic change required to achieve the initial astigmatic goal. The index of success is the ratio of difference vector magnitude divided by the magnitude of the targeted change in astigmatism.

To examine the spherical changes to enable some parallel comparisons to be made, two analogous indices were derived after conversion of the spherical equivalent values to the corneal plane. Two separate spherical parameters were calculated and examined.

1. Spherical correction index:

$$\frac{\text{spherical equivalent correction achieved}}{\text{spherical equivalent correction targeted}}$$

2. Index of success for spherical change:

$$\frac{\text{spherical equivalent remaining (absolute)}}{\text{spherical equivalent correction targeted}}$$

where spherical change relates to spherical equivalents by refraction determined at the corneal plane. Geometric means were calculated for the group.

RESULTS

Our overall visual results at 12 months include all 97 eyes in the study with myopic refractive errors ranging from -1.00 to -15.00 D at the corneal plane (Table).

Spherical Correction

The spherical correction of patients who had correction of myopic astigmatism (PARK) improved

Table
Visual Acuity and Refractive Results 12 Months after PARK in 97 Eyes

	1.0 coeff* (N=32) No. eyes (%)	1.2 coeff† (N=65) No. eyes (%)
± 0.50 D	10 (31)	22 (34)
± 1.00 D	17 (53)	36 (55)
± 2.00 D	26 (81)	54 (83)
	Elliptical (N = 86)	**Sequential (N = 11)**
± 0.50 D	25 (29)	7 (64)
± 1.00 D	44 (51)	9 (82)
± 2.00 D	69 (80)	11 (100)
≥20/20 uncorrected	19 (20)	
≥20/40 uncorrected	55 (57)	

**1.0 coefficient of adjustment—no variation in the magnitude of astigmatism treatment*
†1.2 coefficient of adjustment—astigmatism treatment magnitude increased by a factor of 1.2 (20%) to correct for system undercorrection.

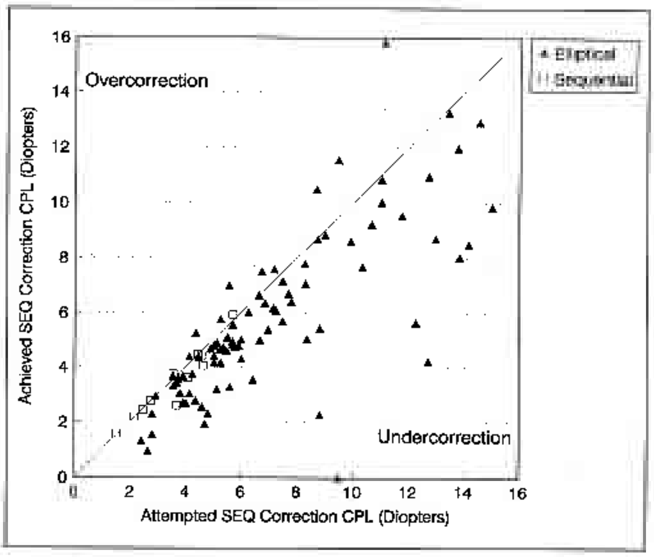

Figure 1: Scatterplot for achieved spherical equivalent refraction versus attempted, separately plotted for elliptical and sequential modes.

insignificantly after the 1.2 adjustment was incorporated. For all eyes at 12 months, the spherical correction index at the corneal plane was 0.83, ie, 83% corrected prior to the 1.2 adjustment, and 0.84 (84% of correction) in eyes after the 1.2 adjustment.

The sequential PARK method showed more accurate spherical corrections than the elliptical mode. When comparing geometric means of patients treated at 12 months, 74% correction was achieved by the elliptical mode, while 89% spherical correction occurred in those treated by the sequential mode. (Fig 1). For all eyes, the index of success for spherical change was found to be 0.21 (SD 0.19); 0.22 (SD 0.19) for the eyes treated with the elliptical mode, 0.16 (SD 0.13) for the eyes treated by sequential mode (P=0.313, t-test). Correction of the spherical refractive error for the group appears more effective than the comparable astigmatic success index when examining this index.

Non-Vector Analysis: Astigmatism

This analysis examines the absolute amounts of astigmatism by refraction, topography, and keratometry over time and is shown in Figure 2A for eyes treated prior to April 1993 without adjustment, and Figure 2B with the 1.2 adjustment. The analysis of the change in these two groups at 12 months by simple subtraction of astigmatism values showed a reduction of astigmatism of 0.75 D (SD 0.59) by refraction, 0.57 D (SD 0.59) by topography, and 0.58 (SD 0.61) by keratometry before the adjustment, and 1.10 D (SD 0.95) by refraction (p=0.016), 0.69 D (SD 0.95) by topography (p=0.532), and 0.67 D (SD 0.88) by keratometry (p=0.603) after the adjustment. A greater reduction is shown by analysis of refraction than by corneal (topographic or keratometric) astigmatism (p<0.0001), and overall a greater reduction for all groups after the adjustment was introduced (p=0.0452).

The elliptical and sequential results for the absolute levels of refractive astigmatism for all eyes has sequential showing greater amounts both preoperatively and at 12 months. Simple subtraction of astigmatism values showing the change from before surgery to the 12 month values, examines the change induced in the existing astigmatism. The elliptical mode showed a reduction of 0.88 D (SD 0.87) in refraction, 0.65 D (SD 0.81) for topography, and 0.62 D (SD 0.81) by keratometry, and sequential 1.83 D (SD 0.84) by refraction (p=0.001), 0.70 D (SD 1.12) by topography (p=0.843), and 0.79 D (SD 0.73) by keratometry (p=0.510). This shows a greater reduction of astigmatism for the sequential modes than the elliptical when measured by refraction, but no discernible difference between the two by corneal values.

Vector Analysis: Astigmatism

Correction Index—When examining treatments performed prior to April 1993[8], the mean surgically induced astigmatism value by refraction was less than the targeted induced astigmatism by a factor 10:12, showing the presence of a system undercorrection. Consequently, a calculated adjustment of 1.2 to all our subsequent astigmatic treatments was made after this date. The mean targeted induced

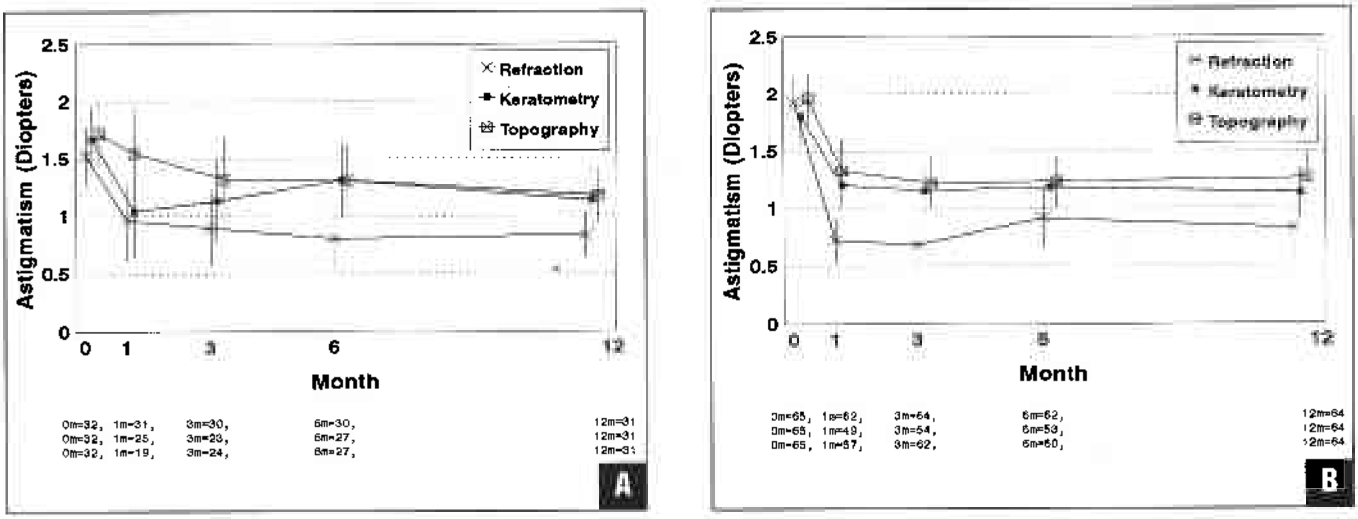

Figure 2: The absolute amount of astigmatism as measured by refraction, keratometry, and topography over time without adjustment coefficient (A) and with the 1.2 adjustment coefficient (B). Number of eyes examined for all three categories at each interval is indicated in the data below.

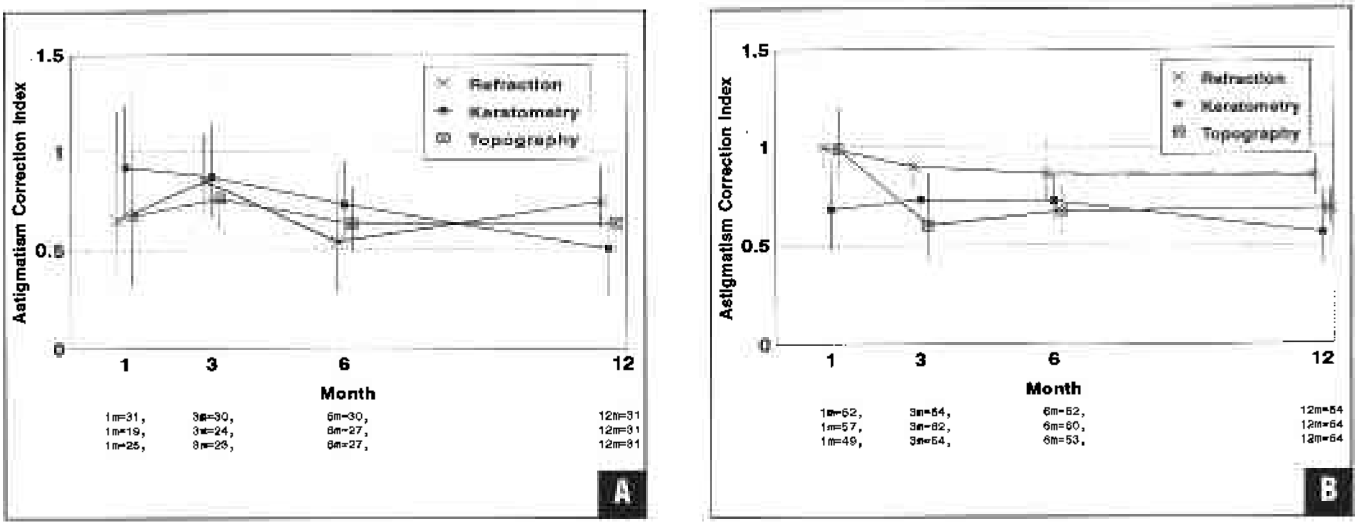

Figure 3: The astigmatism correction index as measured by refraction, keratometry, and topography over time without adjustment coefficient (A) and with the 1.2 adjustment coefficient (B). Number of eyes examined for all three categories at each interval is indicated in the data below.

astigmatism for eyes prior to the 1.2 adjustment was 1.62 D (SD 0.81) (elliptical 1.45 D [SD 0.42], sequential 3.25 D [SD 1.84]) and after this time, 1.96 D (SD 0.90) (elliptical 1.79 D [SD 0.74], sequential 3.13 D [SD 1.14]) (p=0.076). This adjustment of astigmatism treatment magnitude led to less undercorrection, with the surgically induced astigmatism values both by topography and refraction being closer to the targeted induced astigmatism with a correction index closer to unity.

Without any adjustment to astigmatism treatment magnitude prior to April 1993, our 1-year results showed a mean correction index (surgically induced astigmatism divided by targeted induced astigmatism) of 0.74 (SD 1.79) by refraction, 0.50 (SD 3.67) by keratometry, and 0.63 (SD 2.05) by topography. After the 1.2 adjustment, the mean correction index improved to 0.85 (SD 1.62) by refraction (P=0.356), 0.56 (SD 3.84) by keratometry (P=0.848), and 0.68 (SD 1.77) by topography (P=0.730)—closer to the ideal of 1.0 when determined by all modalities (Fig 3). When one examines the results separately for elliptical and sequential treatments, the mean correction index by refraction at 12 months was 0.77 (SD 1.82) for elliptical and 0.52 (SD 1.09) for sequential prior to the 1.2 adjustment (p=0.472). After the adjustment, the astigmatism was more effectively corrected achieving a correction index of 0.88 (SD 1.62) for the elliptical and 0.67 (SD 1.49) for the sequential method.

These results demonstrate increasing undercorrection of astigmatism over time both by elliptical

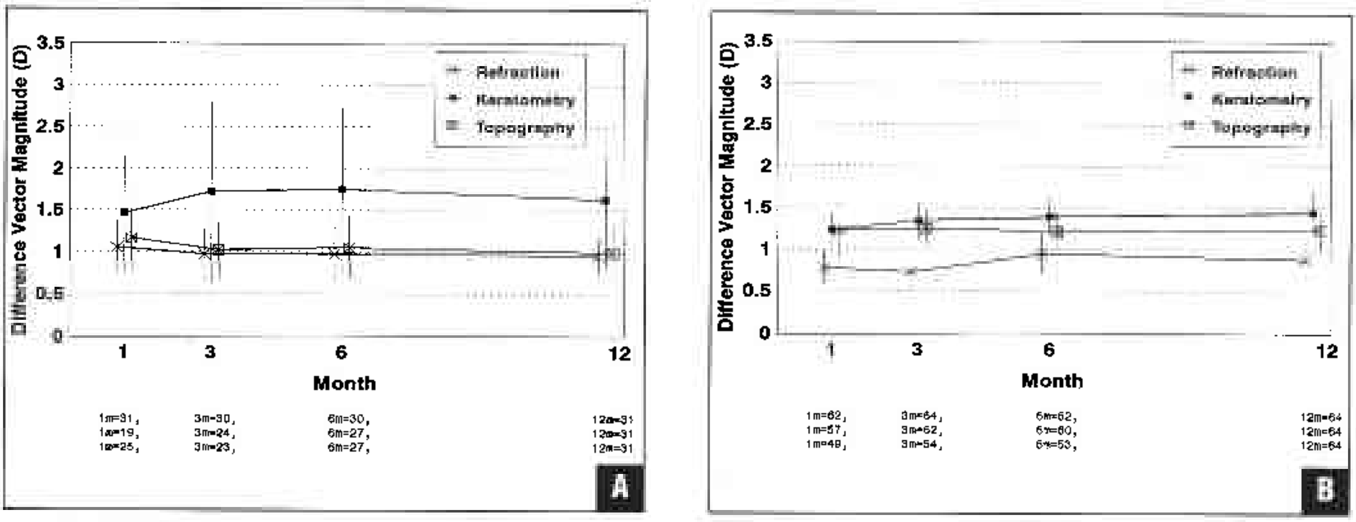

Figure 4: The difference vector magnitude as measured by refraction, keratometry, and topography over time without adjustment coefficient (A) and with the 1.2 adjustment coefficient (B). Number of eyes examined for all three categories at each interval is indicated in the data below.

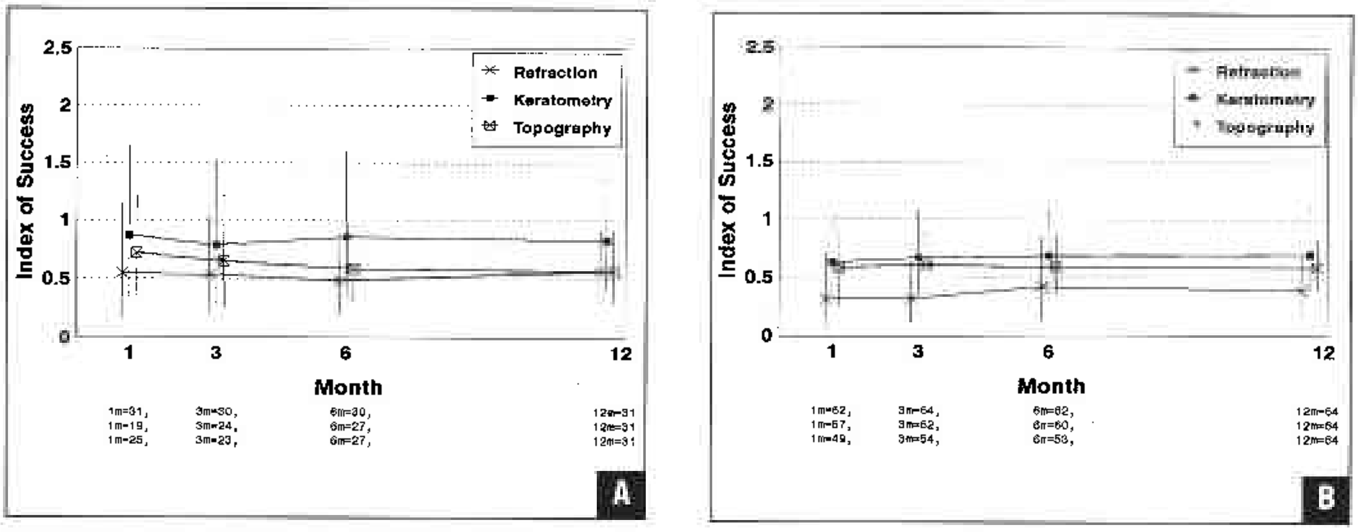

Figure 5: The index of success as measured by refraction, keratometry, and topography over time without adjustment coefficient (A) and with the 1.2 adjustment coefficient (B). Number of eyes examined for all three categories at each interval is indicated in the data below.

and sequential modalities of treatment, with the sequential less effectively correcting astigmatism. After the 1.2 adjustment, measured by refraction, the elliptical treatments showed an undercorrection of 12% (0.88), and the sequential method 33% (0.67), suggested by the above indices. However, the sequential method was used for more challenging eyes, where the amount of cylinder was relatively greater, exceeding the associated spherical myopic error. The trend for progressive undercorrection over time is similar to the common finding when examining changes in spherical equivalents.

Absolute Measures of Success

The difference vector is an absolute measure of the amount of astigmatism remaining uncorrected, independent of the targeted change in astigmatism. A comparison between the 1.0 versus 1.2 adjusted mode of treatment at 12 months showed that prior to the 1.2 adjustment, the difference vector was 0.96 D (SD 0.56) by refraction, 1.63 D (SD 2.29) by keratometry, and 0.99 D (SD 0.86) by topography. After the 1.2 adjustment, the difference vector mean decreased to 0.88 D (SD 0.77) by refraction (p=0.576). An insignificant reduction was shown by keratometry 1.44 D (SD 1.03) (p=0.588), and the difference vector actually increased to 1.23 D (SD 0.84) by topography (p=0.193) (Fig 4).

Relative Measures of Success

The index of success provides a relative value by deriving a ratio of the uncorrected astigmatism

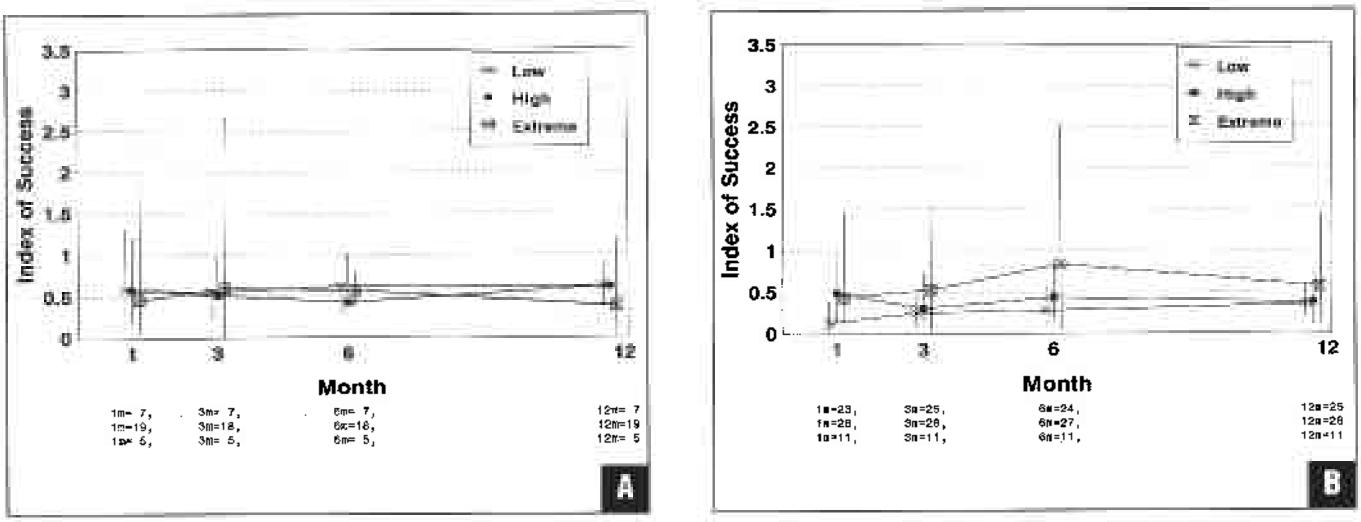

Figure 6: The index of success via refraction of low (0 to -5.00 D), high (-5.00 to -10.00 D), and extreme (-10.0 to -15.00 D) levels of myopia over time without adjustment coefficient (A) and with the 1.2 adjustment coefficient (B). Number of eyes examined for all three categories at each interval is indicated in the data below.

remaining divided by the targeted induced astigmatism. Greater success is shown by a lower value, with zero being the best achievable. The results of the index of success in comparing the 1.0 versus the 1.2 adjusted mode of treatment for all eyes at 12 months showed without any magnitude adjustment (Fig 5A) an index of success of 0.57 (SD 0.06) by refraction, 0.83 (SD 0.10) by keratometry, and 0.57 (SD 0.06) by topography. After the 1.2 adjustment (Fig 5B), the index of success was 0.40 (SD 0.08) by refraction (p=0.005), 0.70 (SD 0.09) by keratometry (p=0.079), and 0.59 (SD 0.04) by topography (p=0.567) demonstrating an overall improvement in the results by the modalities of refraction and keratometry, with refraction improving from a value of 0.57 (SD 0.06) to 0.40 (SD 0.08) (p= 0.005). This latter value for refraction effectively demonstrates a 60% correction of the existing astigmatism achieved after introduction of the magnitude adjustment. It is possible that the failure of topography to detect any quantitative improvement relates to variations in the manner in which numerical values are ascribed to the maps of treated (flattened) corneas.

Comparing the elliptical mode of treatment with the sequential at 12 months by examination of the index of success for all eyes with and without the adjustment, the elliptical mode achieved an index of success of 0.46 (SD 0.09) by refraction, 0.75 (SD 0.10) by keratometry, and 0.58 (SD 0.05) by topography. The index of success for the sequential mode at 12 months showed values of 0.38 (SD 0.02) by refraction, 0.70 (SD 0.09) by keratometry, and 0.62 (SD 0.03) by topography, showing a trend for the sequential group results to be marginally better than the elliptical.

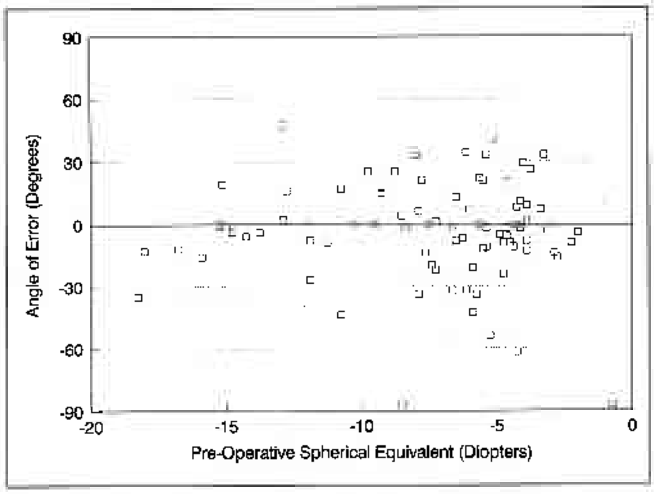

Figure 7: The angle of error as measured by topography.

When measuring the success of the procedure at 12 months after the 1.2 adjustment, and stratifying the results into three groups of spherical equivalent myopia, that is from 0 to -5 D , -5 to -10 D, and -10 to -15 D (Fig 6), the index of success by refraction shows that there was a fairly equivalent result between the 0 to -5 D and the -5 to -10 D groups—low (0.36, SD 0.03) and high (0.38, SD 0.10) myopes.

However, the extreme myopes were less effectively treated for astigmatism after the adjustment (0.57, SD 0.16) than before (0.38, SD 0.13). Before the adjustment, all three groups' results showed no separate trend for the treatment of astigmatism.

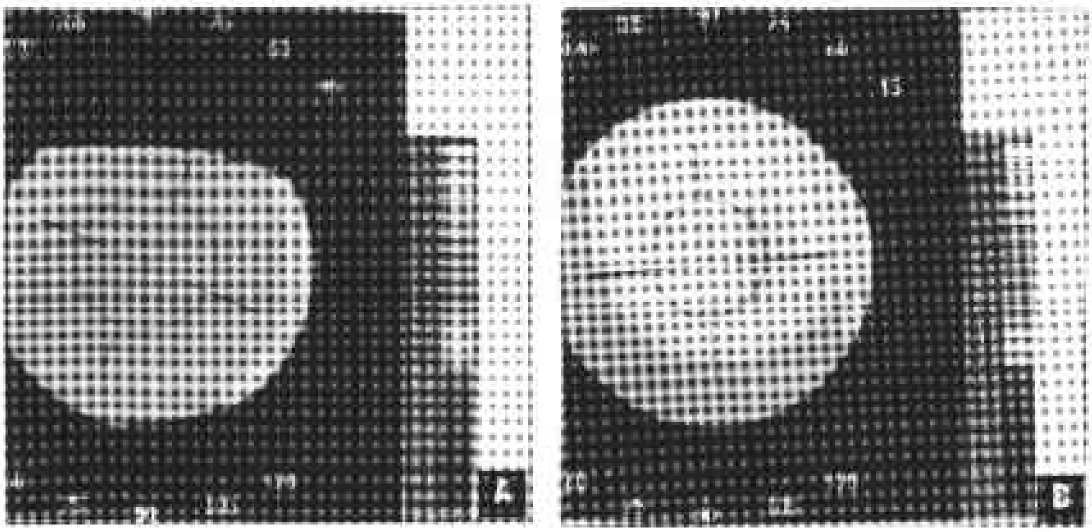

Figure 8: Videokeratography (TMS-1) before surgery (A) shows 0.90 D of astigmatism at meridian 66° and after surgery (B) 1.60 D at meridian 94° after the treatment for 1.04 D x 125°.

Errors in Axis of Treatment

The angle subtended between the applied surgically induced astigmatism and the intended targeted induced astigmatism axis of treatment is the angle of error, which showed a greater spread as shown by the objective results by topography and keratometry than those measured by refraction. For all patients, the mean angle of error at 12 months was reasonably close to the optimal value of zero when measured by all three modalities; +0.78° (SD 19.43°) by refraction, -3.41° (SD 32.75°) by keratometry, and -2.39° (SD 22.04°) by topography (Fig 7).

Adverse Reactions

At 12 months after surgery, 72% of eyes (N=70) had a haze score of nil or 0.5, 26% (N=25) had a haze score between 1.0 and 2.0, and 2% (N=2) had a haze score above 2.0. Seven percent of eyes (N=7) lost two lines of spectacle-corrected visual acuity and 3% of eyes (N=3) lost three or more lines. One patient at 12 months complained of symptoms of starburst at night, probably related to large pupil size and treatment decentration.

DISCUSSION

The ability to effect astigmatic correction with the excimer laser depends on multiple factors which include the computer algorithm used to differentially steepen or flatten the cornea by the laser, proper and steady centration, and uniform corneal wound healing. Remodeling of the anterior corneal surface may also result in changes in the astigmatic status. Spherical PRK does not intend to induce astigmatism. However, the surgically induced astigmatism from treating purely myopic refractive errors with round ablation zones is about 0.48 D (SD 0.53) by refraction and 0.65 D (SD 0.64) by keratometry at 12 months in our patients' eyes, although the magnitude of the induced astigmatism increases with larger corrections. This inadvertent induced astigmatism was first reported in 1993 by two authors of this paper (Alpins NA, Taylor HR. Surgically Induced Astigmatism with the Excimer Laser. ISRK Abstract Current Research: Refractive and Corneal Surgery Symposium 1993; 88). Goggin and associates also reported a mean cylinder power change of 0.75 D in 60 eyes; nine eyes had greater than 1.00 D of surgically induced astigmatism.[14] This inadvertent surgically induced astigmatism has not been shown to have any predilection for any specific orientation, but when present does have an influence on the accuracy of astigmatic ablations when concurrent spherical changes are occurring.

Our results indicate that the magnitude of the astigmatic component of myopic astigmatism can now be effectively treated with the excimer laser, with the correction index now more closely approaching the ideal value by all three modalities of measurement, after the 1.2 astigmatism treatment magnitude adjustment we introduced in April 1993. Newer versions of the VISX VisionKey software now incorporate this coefficient of adjustment.[13] By simple analysis, the amount of astigmatism remaining is greater when measured by topography or keratometry than by refraction, as shown in Figure 2, with simple subtraction showing a

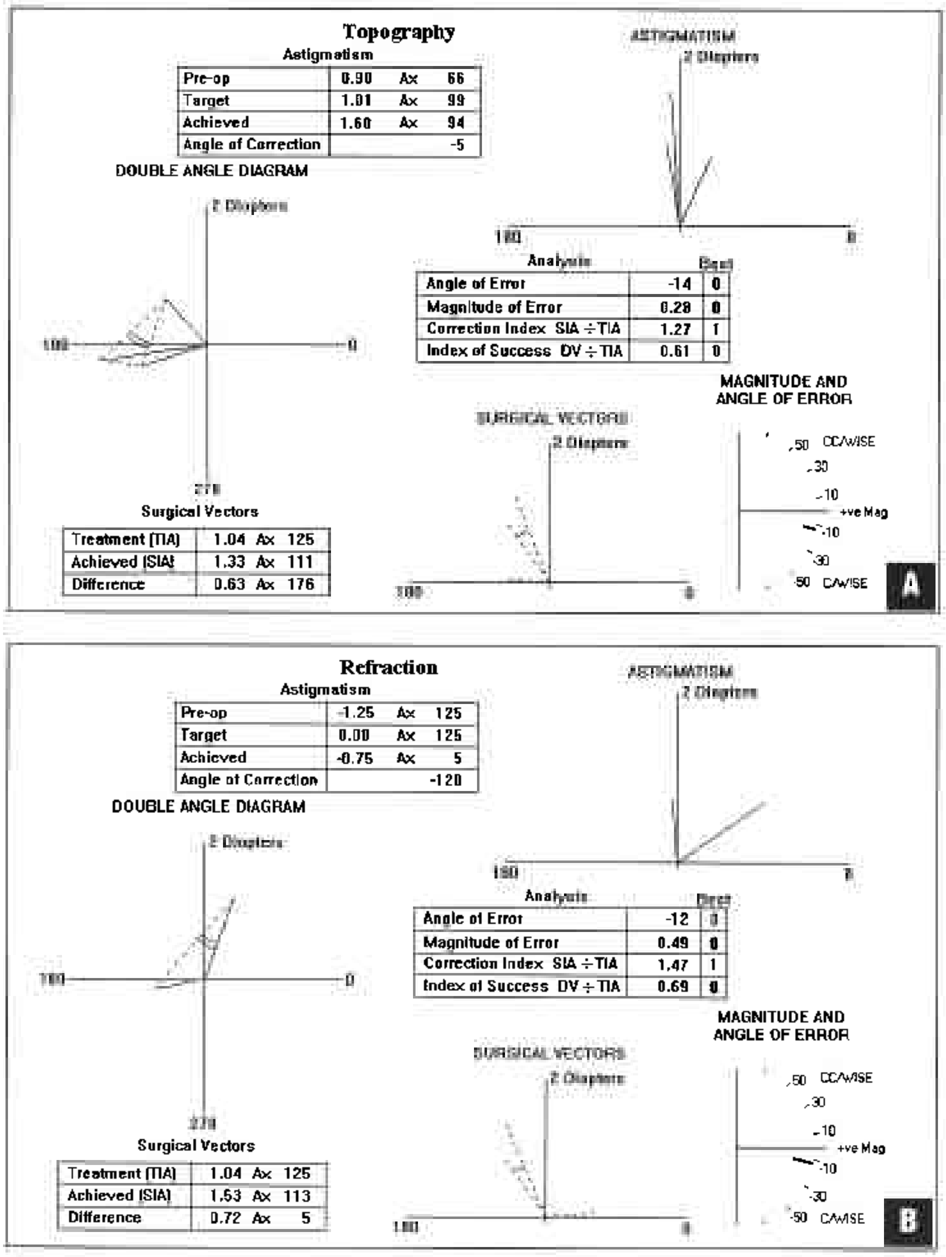

Figure 9. Astigmatism (vector) analysis by topography values (A) and by refractive astigmatism values (B). The Targeted Induced Astigmatism (TIA) is the vector of intended change in cylinder for each treatment and is the common parameter to the two analyses. The Surgically Induced Astigmatism (SIA) is the vector of the actual change that occurred.

Preop and Achieved: measured values.

Target topography: calculated value by applying TIA to preoperative corneal astigmatism.

Target refraction: 0.00 D, ie, elimination of refractive astigmatism.

Treatment (TIA): planned astigmatic treatment.

Achieved (SIA): astigmatic change that results from surgery.

Difference (DV): The magnitude and axis of the untreated astigmatism. Absolute measure of success of astigmatism surgery.

Angle of error: Measure of misalignment of astigmatism treatment.

Magnitude of error: Magnitude difference between achieved SIA and desired TIA astigmatism treatment.

Correction Index (CI): Proportion of astigmatism correction achieved.

Index of Success (IOS): Relative measure of success of astigmatism surgery.

greater reduction in refractive astigmatism than that measured by the corneal values of topography and keratometry. This phenomenon of excess corneal astigmatism remaining compared with refractive may be explained by undue emphasis on refraction as the sole parameter for surgical planning.[15] The treatment of refractive astigmatism at the cornea in patients who have higher amounts of ocular residual astigmatism may actually result in an increase in magnitude of corneal astigmatism remaining after surgery than was present prior to treatment.

An example of this phenomenon in an eye from the study is shown in Figure 8 where the topographic astigmatism (simulated keratometry 0.90 x 66°) (Figs 8A, 9A) differs significantly from the refractive astigmatism value (-7.00 -1.25 x 125°) (Fig 9B) such that the calculated target corneal astigmatism (1.01 x 99°) (Fig 9A) is greater than the preoperative amount, when treatment is to be carried out by refractive astigmatism values. The patient's measured postoperative refraction was -1.25 -0.75 x 5° (Fig 9B) and measured topographic astigmatism was 1.60 x 94° (Figs 8B and 9A). The parallel vector analyses are shown by topography values (Fig 9A) and by refractive astigmatism values (Fig 9B).

Introduction of topography into the surgical plan may improve this imbalance and reduce the disparity between corneal and refractive astigmatism remaining when examining astigmatism outcomes, and, as a result, reduce corneal astigmatism remaining after surgery. Further studies in optimization are necessary to provide information on how best to achieve the optimal balance between the dual goals of achieving zero topographic and zero refractive astigmatism in the surgical plan. An explanation for the differences between topographic and refractive astigmatism values, how they constitute the ocular residual astigmatism, and how this phenomenon impacts the treatment of astigmatism was discussed in a previous paper.[15]

Refraction has been the principal parameter used for postoperative analysis in the past.[15] In this paper, the analysis of results according to the objective corneal measures, as well as refraction, reveals that results achieved after the 1.2 adjustment (Fig 3B)—the correction of astigmatism achieved, measured by keratometry and topography—is less than that measured by refraction. The reliability achieved in the assessment of these results by these objective corneal measures of topography and keratometry revealed larger difference vectors (Fig 4B) and less success (Fig 5B) than that determined by the subjective values of refraction. The introduction of these objective values provides additional information for quantifying astigmatism results for improvement of outcomes.

Limitations exist in the accuracy of measurement of all three astigmatic modalities. Refraction is a subjective test, and by its nature of dependence on the subject's and tester's reliability, may provide variability and inconsistency in its results. This may also be due partly to the coexisting large changes in spherical refractive errors that may cause less attention than deserved to the associated remaining astigmatic error. Results are shown to vary between keratometry and topography. Keratometry has the potential for reduced reliability created by observer variability that potentially may occur in the manual identification of the steepest corneal axis reliant on the alignment of optical mires. Corneal topography is an evolving technology that attempts to provide automated and objective magnitude and meridian values for astigmatism. However, these devices can vary by not consistently identifying the same preoperative axis in the presence of non-orthogonal astigmatism. Also, postoperative difficulties can be encountered by not clearly identifying a consistent corneal steep meridian where general corneal flattening has occurred in association with the differential astigmatic change. The differences existing between preoperative and postoperative values of corneal and refractive astigmatism values accounts for differences in trends between the parallel analyses employing refractive, topographic, and keratometric astigmatism values.

There is also potential for bias in this sample where patients suffering from visual symptoms may have a higher incidence of topographical abnormalities, which might consequently have a higher rate of presentation for re-examination than patients without any untoward symptoms. This might explain visual and refractive results that are inferior to comparative series from the same center.[16]

PARK is also effective in treating myopia. The visual results in this paper include all eyes treated with spherical equivalent refractions up to -15.00 D sphere at the corneal plane. Vector analysis provides the ability to separate the results achieved during concurrent astigmatic treatment from those separate changes occurring from the treatment of spherical refractive error. Tests such as visual acuity and contrast sensitivity measure multiple aspects of refractive surgery changes including such variables as corneal haze, corneal irregularity, and differing macular function, and do not address such preoperative variables such as differing spectacle-corrected visual acuities. These tests alone do not provide an adequate ability to differentiate between differing astigmatic modes of treatment.

So why are the results in our treatment magnitude of correction satisfactory, but our overall index of success only 0.46 (SD 0.09) by refraction when treating astigmatism? The reason for this can be found in the orientation of the surgically induced astigmatism in relation to the targeted induced astigmatism, ie, the angle of error, in 12-month follow-up results. In the group who benefited from the 1.2 adjustment to magnitude, although the mean angles of error are near zero, the standard deviations are nearly 30° wide. Where the axis misalignment reaches 30°, only 50% of flattening effect at the intended axis is achieved, and at 45°, no flattening effect results. Axis misalignment greater than 45° will increase the astigmatism of the eye.[17] The wide standard deviations (Fig 7) show a fairly wide distribution from -90° to +90° for all modalities—topography being similar to that by keratometry and refraction. Hence, the 1.2 adjustment in treatment of astigmatism reduces undercorrection, but results demonstrate that there is potential for future improvement in astigmatism surgery by improving accuracy in the axis of applied treatment.

This goal may be achievable by better identification of the steepest corneal meridian at the time of surgery, more accurate laser beam alignment, ensuring completeness of epithelial removal when performing PARK. However, indirect factors related to corneal epithelial healing regularity may be modified by improved methods for its modulation. The cornea, potentially, may undergo less disturbance by a closer alignment of the axis of treatment to the topographical meridian, where differences exist between the refractive and topographical astigmatism orientations. However, by employing analogous analyses that enable comparison of uncorrected refractive errors between spherical and astigmatic treatments, the overall index of success results suggest spherical treatment (0.21) is more effective than correcting astigmatic refractive error (0.45).

The examination of a surgical outcome of the astigmatism component associated with myopia has shown an improvement occurring since the introduction of a systematic adjustment by a factor of 1.2 for the undercorrection of astigmatism. Differences exist between elliptical and sequential modes of astigmatism treatment, both in their effectiveness in treating astigmatism and the amount of associated spherical change that occurs. However, by employing parallel indices, described in this paper, success in the treatment of astigmatism lags behind our ability to treat spherical myopia with the excimer laser. Shortcomings exist in astigmatic treatments evident by a remaining angle of error, which if greater than 30°, will more than halve the flattening effect at the intended meridian.

Astigmatism analysis enables refractive surgeons to assess results and determine the most appropriate means to improve the outcome of treatment. The performance of this task using both simple and vector analysis provides additional information on trends that are not otherwise readily apparent. The inclusion of objective astigmatism measures of corneal shape—such as topography or keratometry values—provides valuable additional information both in surgical planning and the examination of the results of astigmatism surgery. The inclusion of these parameters with that of refractive astigmatism enables a comprehensive analysis of astigmatism treatments.

REFERENCES

1. Thompson KP, Steinert RF, Daniel J, Stulting RD. Photorefractive keratectomy with the Summit excimer laser: The phase III U.S. results. In: Salz JJ, McDonnell PJ, McDonald MB, eds. Corneal Laser Surgery. Mosby Year Book; St. Louis, MO;1995:57-63.
2. McDonald MB, Talamo JH. The experience in the United States with the VisX excimer laser. In: Salz JJ, McDonnell PJ, McDonald MB, eds. Corneal Laser Surgery. Mosby Year Book; St. Louis, MO;1995:45-55.
3. McDonnell P, Moreira H, Clapham T, D'Arcy J, Munnerlyn CR. Photorefractive keratectomy for astigmatism: initial clinical results. Arch Ophthalmol 1991;109:1370-1373.
4. Taylor HR, Guest CS, Kelly P, Alpins NA. Comparison of excimer laser treatment of astigmatism and myopia. Arch Ophthalmol 1993;111:1621-1626.
5. Dausch D, Klein R, Landesz M, Schroeder E. Photorefractive keratectomy to correct astigmatism with myopia or hyperopia. J Cataract Refract Surg 1994;20(suppl):252-257.
6. Kim Y, Sohn J, Tchah H, Lee C. Photoastigmatic refractive keratectomy in 168 eyes: six month results. J Cataract Refract Surg 1994;(suppl)20:387-391.
7. Spigelman AV, Albert WC, Cozean CH, Johnson DG, McDonnell PJ, Pender PM, Shimmick J. Treatment of myopic astigmatism with the 193 nm excimer laser utilizing aperture elements. J Cataract Refract Surg 1994;20(suppl): 258-261.
8. Taylor HR, Kelly P, Alpins NA. Excimer laser correction of myopic astigmatism. J Cataract Refract Surg 1994; 20(suppl):243-251.
9. Hersch P, Patel R. Correction of myopia and astigmatism using an ablatable mask. J Refract Corneal Surg 1994;10(supp):S250-S254.
10. Cherry P, Tutton M, Bell A, Neave C, Fichte C. Treatment of myopic astigmatism with photorefractive keratectomy using an erodible mask. J Refract Corneal Surg 1994;10(supp): S239-S245.
11. Tabin GC, Alpins NA, Aldred GF, Carson CA, Taylor HR. Astigmatic change one year after treatment of myopia and myopic astigmatism with the excimer laser. J Cataract Refract Surg 1996; 22:924-930.
12. Loewenstein A, Lipshitz I, Lichtenstein F, Ben-Sirah A, Lazar M. The effect of spherical photorefractive keratectomy on myopic astigmatism. J Refract Surg 1995;11(suppl):S263-S264.
13. Alpins NA. A new method of analysing vectors for changes in astigmatism. J Cataract Refract Surg 1993;19:524-533.
14. Goggin M, Algawi KI, O'Keefe M. Astigmatism following photorefractive keratectomy for myopia. J Refract Corneal Surg 1994;10:540-544.
15. Alpins NA, New method of targeting vectors to treat astigmatism. J Cataract Refract Surg 1997; 23:65-75.
16. Alpins NA, Taylor HR, Kent DG, Lu Y, Liew M, Couper T, McGough V. Three multizone photorefractive keratectomy algorithms for myopia. J Refract Surg 1997;13:535-544.
17. Alpins NA. Vector analysis of astigmatism by flattening, steepening and torque. J Cataract Refract Surg 1997; 23:1503-1514.